A Comparison of Mapping Methodologies Identifying Transportation Disadvantaged Populations and Extreme Weather Risk in Boston

A thesis submitted by

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in partial fulfillment of the requirements for the degree of

Master of Arts

In

Urban and Environmental Policy and Planning

Tufts University

May 2020

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ABSTRACT

This thesis compares three increasingly granular mapping methodologies—Choropleth, Intelligent Dasymetric Mapping, and the Cadastral-Based Expert Dasymetric System (CEDS)— to predict where transportation disadvantaged (TD) populations live in the Boston area. It explores extreme weather risk by estimating TD populations living within evacuation zones or within a reasonable walk to a shelter. Lastly, this thesis includes interviews with representatives from high TD communities and agencies involved in emergency management.

The CEDS results suggest approximately 20% more people may require evacuation assistance than the Massachusetts Emergency Management Agency estimates. In total, 14% of the population in the study area (487,389 people) has a high propensity to be TD. The interviews suggest that organizations are dedicating resources to emergency communication and infrastructure resilience, but specific attention to TD populations could be increased. In the future, planners could utilize this mapping, paired with outreach and training, to proactively plan for extreme weather events.

Acknowledgements

This thesis would not have been possible without the enduring support of my advisor, Sumeeta Srinivasan. Thank you for the seemingly endless time you spent in the Data Lab helping me work through the quirks of ArcMap. Thank you to my reader, Mark Chase, for providing thoughtful feedback and a sounding board for initial research ideas. Thank you to Melanie Gárate for sharing her wealth of connections with me and being the best interview buddy I could ask for. Thank you to the representatives from the Chelsea Department of Planning and Development, the Codman Square Neighborhood Development Corporation, the Massachusetts Bay Transportation Authority, and the Department of Homeland Security for offering their perspectives and sharing their professional knowledge. Lastly, thank you to my friends and family for their words of encouragement and unending support.

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1. Introduction

As the effects of climate change are exacerbated, the frequency of extreme weather events will increase. Many of these events, be they wildfires, hurricanes, or floods, will necessitate the evacuation of large populations. For those populations with access to personal vehicles, the evacuation process may be rather simple. Of course, information campaigns and smart transportation planning will be necessary, but these populations will have the means to remove themselves from evacuation areas. For those who do not own cars, or who are otherwise transportation disadvantaged, evacuation procedures could be much more complicated.

Transportation disadvantaged (TD) populations are sometimes referred to as low-mobility, vulnerable, or carless populations. TD is a metric that combines socioeconomic, environmental, and behavioral factors, including populations who are carless (whether by choice or not), minority, low income, elderly, disabled, those with limited mobility or health problems, homeless, children without adults present, or those with limited English proficiency (USGAO 2006, 15; Renne, Sanchez, and Litman 2011, 420). Several of these factors are correlated, and therefore can exacerbate the level of TD for populations exhibiting more than one factor.

There are several challenges in planning for the evacuation of these populations; the primary challenge is simply identifying where these populations are located. The multitude of factors that contribute to TD, coupled with the difficulty of pinpointing populations at scales more granular than typical census geographies, make it very difficult to know exactly where these populations may be living. Several mapping techniques have been used to estimate TD and other vulnerable populations, yet there is no standardized method.

Additional challenges include the vast diversity of needs required by TD populations, including medical or mobility assistance, as well as legal obstacles and social barriers to evacuating. Due to these vulnerabilities, TD populations require special attention when it comes to evacuation planning.

This thesis addresses the following research question: where are TD populations with respect to extreme weather risk in the Boston metropolitan area? Additional objectives include addressing the following questions:

- Where are transportation disadvantaged populations located in the Boston metropolitan area?
- What mapping methodology best represents the location of these populations?
- What does evacuation planning for transportation disadvantaged populations look like at a federal, state, and community level?
- In those communities which contain a large transportation disadvantaged population, what plans are in place to assist these populations during an evacuation?
- How can state and local governments better serve these populations during extreme weather events?

This thesis begins with a thorough literature review of peer-reviewed, government, and grey literature related to TD, evacuation planning, population mapping, climate justice, and the intersection of these areas.

TD reveals itself to be a complicated metric, with changing definitions over time to include additional vulnerable populations. To this day, there lacks a universal understanding of what it means for someone to suffer from "transportation disadvantage." At its core, TD is a mobility and climate justice issue, and often the result of larger forces of long-term state domination or discrimination. Viewing TD through the lens of evacuation planning shows how acute this problem can be in many parts of the world.

A review of federal and state level disaster management in the United States places this problem in context. A look at the recent history of disasters demonstrates that a renewed attention to TD populations occurred following Hurricane Katrina, which severely impacted Louisiana and Mississippi in August 2005. Several government reports released following this disaster outlined the need for better planning for TD populations and faster response and financial assistance from the federal government when disasters occur. In the state of Massachusetts, evacuation plans are focused on hurricanes, as they are the most likely disasters to affect New England. The Massachusetts Emergency Management Agency (MEMA) is responsible for evacuation planning and prepares a specific plan for populations with Critical Transportation Need. The statewide plan does recognize the difficulty in identifying these populations, but only offers a few brief suggestions for how a municipality should attempt to do so (MEMA 2019b, 11).

The literature review concludes with an outline of the many challenges of evacuation planning for TD populations, a summary of previous mapping methodologies used to identify vulnerable populations, and the relevance of TD populations today.

This thesis goes on to utilize three mapping techniques in an effort to compare identification methodologies and refine a process that best represents where TD populations are located. The methods are as follows: (1) A standard choropleth method, which utilizes a binary system to determine levels of TD and a thematic shading symbology, (2) a dasymetric mapping method utilizing the Environmental Protection Agency's Intelligent Dasymetric Mapping (IDM) Toolbox to redistribute population based on land use, and (3) a Cadastral-Based Expert Dasymetric System (CEDS) which utilizes parcel data to redistribute population along with a principal component analysis of vulnerability attributes. In addition to these three methods, this research includes an analysis of populations within hurricane evacuation zones and within 10, 15, and 20-minute walks of emergency shelters.

This thesis also includes results from semi-structured interviews conducted with representatives from community organizations in particularly vulnerable neighborhoods and from state agencies involved in emergency planning. The purpose of the interviews was to ground truth the mapping results, as well as to understand the evacuation resources for these populations at a local and state level.

Each consecutive mapping methodology improves in accuracy and detail, both visually and quantitatively, as the methods utilize increasingly finer-grained layers and processes to represent population distribution and levels of TD. However, despite differences in population distribution, each method overwhelmingly identifies the same cities and neighborhoods within the study areas as having high levels of TD.

An analysis of TD populations living within evacuation zones or within 10, 15, or 20-minute walks to emergency shelters demonstrates that the CEDS method estimates much higher proportions of TD populations living within these areas than the Choropleth or IDM methods. According to this method, 14% of the population in the study area has a high propensity to be TD, and of these people, 14% live within an evacuation zone *and* farther than a 20-minute walk from a potential shelter. Compared with estimates from MEMA, which assumes only 6% of the population in evacuation zones A and B could require assistance, these numbers are significantly higher and could represent a severe underestimation in the amount of people that could require evacuation assistance.

Interviews with representatives from community and state-level organizations revealed a real concern for extreme weather and climate resiliency. All organizations expressed concerns for the effects extreme weather could have on energy and transportation systems and how potential outages or lapses in service could affect the delivery of social or medical services. Increased community involvement, public education, training, government agility, and IT resiliency strategies were proposed as ways to increase the resiliency of communities during extreme weather events.

While TD and other vulnerable populations are certainly not ignored by MEMA and other organizations, it remains unclear how they are specifically estimated and accounted for in evacuation planning. Therefore, the mapping analyses discussed in this thesis could help planners more accurately predict areas with high TD and to appropriately tailor evacuation plans and target resources to ensure that help is provided to those who require assistance. These methods can be performed using publicly available census and parcel data and relatively simple spatial analysis tools. In addition to conducting mapping analyses, evacuation planning for TD populations should be combined with other identification methods, such as in-person outreach, registries, or surveys, that will allow identification on a household level.

My hope is that the results of this research can help emergency planning professionals proactively prepare for evacuation scenarios, and to ensure that all residents are able to safely and efficiently evacuate, regardless of car ownership, age, ability, income, or race.

2. Literature Review

Transportation Disadvantage

Transportation disadvantage (TD) is an elusive metric. Otherwise referred to as low-mobility, vulnerable, or carless populations, TD can be described as a combination of many factors, some socioeconomic, some environmental, and others behavioral. It generally refers to those populations which experience "limits on or barriers to access to destinations such as employment, education, health care and nutritious foods" (Shay et al. 2016, 129). It is similar to "stranded mobility," described as a "situation of constrained mobility and poor accessibility," and often exacerbated "where extreme environmental events separate poorly resourced populations from their normal range of venues and activities" (Grieco and Hine 2016, 65). TD populations commonly include those who are carless (whether by choice or not), minority, low income, elderly, disabled, those with limited mobility or health problems, homeless, children without adults present, or those with limited English proficiency (USGAO 2006, 15; Renne, Sanchez, and Litman 2011, 420). The exhibition of any one of these factors does not guarantee the existence of TD. Rather, TD is a consequence of socioeconomics, as well as location and available infrastructure (Shay et al. 2016, 137). Access to transportation systems, such as public transit, infrastructural or geographical barriers, such as bridges or sidewalk availability, and social connectivity can all play a role in TD.

Over time, the definition of TD and other vulnerable populations has changed and expanded. Initially referring only to those populations requiring major medical support, it has now come to include those who require other forms of care, such as the elderly, disabled, or chemically dependent (Turner et al. 2010, 160). However, no standard definition exists. A 2009 telephone survey of 11 state and local emergency management agency offices revealed the wide range of definitions of “special needs population” (Turner, Lindly, and Kumlachew 2010, 9). While some states included just those with medical problems, others included carless and elderly populations, among others. In addition to nonstandard definitions, the populations defined as TD are constantly shifting due to changes in economic, health, or mobility status (USGAO 2006, 15). Perhaps more importantly, these populations are growing as the baby boomer generation ages (Turner et al. 2010, 160).

Populations may exhibit just one of the above TD factors or several at a time. For example, a large proportion of carless populations also have other conditions requiring medication or medical support (Renne, Sanchez, and Litman 2011, 422). Therefore, it is more likely that TD populations exhibit several of the above factors at once, putting them at an even greater disadvantage. Besides simply hindering movement about a place, TD can also contribute to economic, social, and political isolation as resources are generally harder to access. Those who experience TD may be prevented from accessing jobs, schooling, healthcare, or fresh food, contributing to a lack of wealth building opportunities, health risks, or social exclusion. Some researchers have utilized survey data to model the direct relationship between TD and social exclusion, as well as its downstream effects on well-being (Currie and Delbosc 2010; Delbosc and Currie 2011).

In addition, certain factors of TD have the potential to exacerbate other factors. For example, low income populations are more likely to work non-standard hours, during which public transit systems are less likely to run regularly, therefore, increasing the level of TD. Similarly, those who are disabled are more likely to earn lower incomes, and therefore live in areas lacking infrastructure and experiencing higher emergency risk (Renne et al. 2009, 37). It is clear that TD has a much larger impact than simply making it hard to move about a city.

At its essence, TD boils down to a mobility and climate justice issue. TD populations are subject to “differential vulnerability” or in other words, different levels of risk and vulnerability than other populations (Barrow 2017, 5; Donner and Rodriguez 2011). Therefore, those experiencing TD and other forms of economic, sociopolitical, or racial discrimination are often unequally affected by the causes, impacts, and policies of climate change, including extreme weather events (Harlan et al. 2015). Low-income and minority populations, many of which already suffer some level of TD, have historically been confined to residential areas of high flood risk and low infrastructure investment (Barrow 2017, 2). There is often an element of state domination and politics to the geographic distribution of TD (Cook and Butz 2016). Therefore, place—and a place's accessibility and potential for mobility—plays an important role in economic outcomes, social capital, local governance, and opportunities for civic participation (Rumbach, Makarewicz, and Németh 2016).

A comparable index is social vulnerability. Like TD, social vulnerability is a function of both demographic and socioeconomic characteristics, as well as access to resources and location. It refers specifically to the vulnerability of groups to the impacts of hazards, their disproportionate suffering, and their lack of resiliency to recover (Martin 2015, 53). Many of the same groups considered to be TD can also be socially vulnerable (children, elderly, low-income, etc.).

While measuring TD is difficult, several researchers have attempted to do so using a variety of methods. Pyrialakou et al. outline measures that are both process-based, such as analyses of accessibility, deprivation, or mobility, and measures that are outcome-based, such as analyses of realized travel behavior (Pyrialakou, Gkritza, and Fricker 2016). They suggest using a combination to best represent areas of TD. More generally, some studies simply explore access to public transit, using a variety of indices and accessibility measures (Saghapour, Moridpour, and Thompson 2016).

When it comes to reducing TD in an urban environment, a common solution is to focus on enhancements to public transportation systems, via new routes, increased frequency, or reduced ticketing fees. Increasing access to these systems can greatly increase mobility for carless populations. For those populations that may require special attention, such as children and the disabled, it is important for cities to provide transit that attends to their specific needs (for example, paratransit). However, it is always difficult to reconcile the competing goals of *coverage*, or providing service that extends to all members of a community, and of maximizing *ridership* within limited resources (Walker 2012, 118). These tradeoffs almost always affect populations living in areas that may not attract high ridership but are in dire need of better transit options. Pereira et al. argue that concerns over the distribution of TD should focus on distributive justice through the lens of accessibility (Pereira, Schwanen, and Banister 2017). Using several theories of justice, they argue that context-specific, minimum levels of transport access should be established, and that transport interventions should prioritize increasing access for vulnerable groups. They importantly note that accessibility refers to both a "capability to access and use mobility technologies and transport systems/vehicles" and the "capacity to access desired places and opportunities" (Pereira, Schwanen, and Banister 2017, 183).

A range of other solutions can address the other contributing factors related to TD, such as economic assistance, job training, access to healthcare, complete streets policy, or the provision of affordable housing. As a metric with a wide range of influences, solutions must be multi-faceted as well.

Disaster Management in the United States

In the United States, evacuation planning is coordinated at the federal level by the Department of Homeland Security (DHS). Housed within DHS is the Federal Emergency Management Agency (FEMA), whose mission is “helping people before, during, and after disasters” (FEMA 2019a). FEMA is responsible for disaster preparation, prevention, mitigation, response, and recovery; in this context, “disaster” may refer to natural or man-made events, including acts of terror. FEMA was created in 1979 in an effort to consolidate disaster management. The Disaster Relief Act had been passed four years earlier, granting the power of Presidential disaster declarations, but there were still over 100 different disaster agencies. FEMA officially became part of DHS in 2003.

In 1988, the Robert T. Stafford Disaster Relief and Emergency Assistance Act was signed into law, establishing the system by which emergency declarations prompt financial and physical assistance through FEMA, following a governor’s request. This act also established a new philosophy of emergency management, outlining that disasters should be managed at the lowest possible level. The idea is that emergency management should begin on the frontlines, with local police, fire, public health and medical, and emergency management personnel taking charge. Only if needed, and explicitly requested, will federal support be administered. Federal support may be given in the absence of an official request but this is uncommon (USGAO 2006, 12). This philosophy is reflected in FEMA’s National Incident Management System, in which a “whole community” approach is taken, meaning in addition to trained government officials, individuals, businesses, community organizations, non-profits, schools, and other organizations hold a shared responsibility for disaster preparedness (FEMA 2018b, FEMA 2019b). In a similar vein, FEMA partners with other federal agencies, including the Department of Transportation (DOT), in evacuation planning and procedures.

EVACUATION PLANNING FOR TD POPULATIONS AT A FEDERAL LEVEL

Hurricane Katrina made landfall over Louisiana and Mississippi on August 29, 2005. As the most destructive natural disaster in US history, it resulted in an estimated 1,330 deaths, with 71% of victims older than 60 and 47% over 75. (Townsend, 2006; Louisiana Department of Health and Hospitals, 2006). While the contraflow highway plan was quite efficient and successful in safely evacuating residents in personal vehicles, those who did not have access to cars, or were otherwise transportation disadvantaged, did not have many options. For example, a survey of storm victims conducted by Harvard Medical School found that black respondents and high school dropouts were less likely to evacuate, likely due to constraint rather than choice (Thiede and Brown 2013, 820). At the time of the storm, an evacuation plan using Amtrak trains and city buses was in the works, however it had not yet been implemented; in addition, hundreds of transit vehicles were destroyed in the flooding (Renne 2006).

The storm became a wake-up call for the DHS, and many others involved in evacuation planning. A slew of reports and reviews were conducted, including *The Federal Response to Hurricane Katrina: Lessons Learned*, published by The

White House, *Transportation-Disadvantaged Populations: Actions Needed to Clarify Responsibilities and Increase Preparedness for Evacuations,* published by the United States Government Accountability Office (USGAO), and *Hurricane Katrina: A Nation Still Unprepared,* published by the Senate Committee on Homeland Security and Governmental Affairs. These reports examined the response to the storm in an effort to adjust policies and plans going forward.

In August 2006 the Post-Katrina Emergency Management Reform Act (PKEMRA) was passed, restructuring FEMA, aiming to clarify its responsibilities, and streamlining collaboration with lower levels of government (FEMA 2018a). This Act allowed the federal government to provide accelerated assistance and support if needed. PKEMRA also established an Office of Disability Integration and Coordination, dedicated to ensuring people with disabilities are adequately addressed in the planning, executing, and communicating of evacuation procedures (FEMA 2018a). This built off the Executive Order 13347, *Individuals with Disabilities in Emergency Preparedness*, which attends particularly to emergency planning for disabled employees of federal agencies and departments (USGAO 2006; U.S. Department of Labor, n.d.). At a broader level, it is required that metropolitan planning organizations consider race, ethnicity, and environmental justice (EJ) in their transportation planning processes (Barrow 2017). In addition, any program receiving federal funds must abide by the Civil Rights Act, which outlaws discrimination on the basis of race, color, or national origin (Barrow 2017).

The Federal Highway Administration recommends that transportation agencies can protect EJ communities from climate change through “stakeholder inclusion, proactive planning, risk mapping, and the careful consideration of community needs in emergency operations procedures” (FHWA 2016, 1). However, the nature of disaster response often results in a compressed timeline for agency decisions and funding requests, “leapfrog planning” in which agencies prioritize certain initiatives over previously planned projects due to funding eligibility requirements, and “project selection tunnel vision”; these elements can prevent the implementation of forward-looking resilience projects, especially those that consider TD populations (Frick and Forscher 2018, 10). While these policies address some factors of TD, they do not necessarily include all TD populations.

The USGAO report mentioned above focused exactly on this issue. This report sheds light on the lack of planning for TD populations due to two main challenges: the difficulty of identifying and locating TD populations, and the process of determining specific needs and providing applicable transportation (USGAO 2006, 7). These challenges are perpetuated by a lack of clear requirements, funding, and guidance in preparing for these populations. The report generates several recommendations, including further clarifying federal agency responsibilities and lead roles, requiring DHS and DOT grant recipients to plan for TD populations, and encouraging knowledge sharing among states and localities planning for emergencies.

Evacuation Planning for TD Populations at a State and Metro Level

The Massachusetts Emergency Management Agency (MEMA) is the state agency responsible for emergency preparedness and planning; it coordinates with other agencies at the federal, state, and local levels, as well as non-profits and businesses to plan for and respond to emergencies (Mass.gov 2019b). One of MEMA's many responsibilities is to prepare and maintain a variety of emergency management plans, including the *Commonwealth of Massachusetts Statewide Evacuation Coordination Plan*. This plan follows the framework of FEMA's National Incident Management System, with a focus on local response, and it outlines the statewide policies, definitions, coordination actions, and agency responsibilities (MEMA 2019b). In support of this plan, the state has designated 16 Massachusetts Emergency Support Functions in areas ranging from transportation to firefighting to search and rescue.

As an Annex to this comprehensive plan, MEMA also publishes a plan focused on evacuation operations for populations with Critical Transportation Need (CTN). MEMA defines CTN populations as the "segment of the population that lacks personal transportation and requires government-provided transportation assistance to evacuate out of an at-risk area to a designated shelter" (MEMA 2019a, 6). This plan assumes that 2% of the population in hurricane evacuation zone A and 1% in zone B will require assistance in a "notice incident" such as a hurricane. In a "no-notice incident" it estimates 6% of the population in these zones will require assistance (MEMA 2019a, 16). These figures are based on the results of a 2013 phone survey in which only 300 respondents answered a series of questions about evacuation assistance (MEMA 2019a).

In addition to providing these figures, the CTN plan outlines how a municipality is responsible, at minimum, for providing transportation assistance to CTN evacuees either from their private residences or from an Evacuation Assembly Point (EAP) to a local shelter. EAPs are designated locations to which CTN populations will be directed in the event of a large evacuation. Therefore, each municipality is individually tasked with identifying CTN populations, informing them of evacuation procedures, and if necessary, arranging for their transportation.

Although these two MEMA plans outline detailed processes for transporting evacuees from EAPs to Transportation Hubs (T-Hubs) onto Regional Reception Centers, there is minimal instruction on how to accurately identify where TD populations are located and where local agencies should locate these EAPs and T-Hubs. MEMA recognizes the difficulty in identifying these populations, but only offers brief, suggestive methods for how to accomplish this task (MEMA 2019b, 11). These include the use of hot lines, local registries, well-being checks, and partnerships with organizations that provide services to individuals with disabilities (MEMA 2019a, 39). While these are helpful recommendations, they are not prescriptive, and minimal details are offered to assist municipalities in implementing these processes.

Perhaps identification is complicated by the fact that MEMA treats CTN populations, populations in health care facilities, Access and Functional Needs populations (ANF), and unaccompanied minors separately. The state recognizes ANF populations as “people with disabilities, people who live in institutionalized settings, elderly, children, people from diverse cultures, people with limited English proficiency/non-English speakers, and people who are transportation-disadvantaged" (Mass.gov 2019a).

Many resources are available online, via Mass.gov or Ready.gov (the federal emergency preparedness website), for these populations. There is a great emphasis on self-preparedness and sufficiency; however, there are services available, such as emergency preparedness training and a 2-1-1 hotline, to assist these populations in preparing for disasters and potential evacuations. In addition to state organized assistance, community-based evacuation assistance organizations, called Community Organizations Active in Disasters (COAD) exist. These are an offshoot of a national program (Voluntary Organizations Active in Disasters) and consist of agencies and groups willing to assist in evacuation preparedness and response (FRCOG 2014). Currently, two COADs operate in Massachusetts, one in Berkshire County and another in the Pioneer Valley.

Other states and cities have instituted similar planning measures to adequately address TD populations in evacuation planning. However, some have fallen short. In 2011, the city of Los Angeles, CA was sued for failing to include people with disabilities in their evacuation planning (Disability Rights Advocates 2011). A similar suit followed in 2013 in New York City (Disability Rights Advocates 2013). Both decisions resulted in concrete actions that the cities had to take to ensure these populations were included in planning.

The Challenges of Evacuation Planning for TD Populations

Since Hurricane Katrina, there has been a significant amount of scientific and policy research examining the challenges and strategies in planning evacuations for TD populations. Today, over a decade after the storm, many of these challenges still remain.

As stated in the USGAO report, the challenges of planning for TD populations begin with the difficulty in simply identifying and locating these populations. Many factors contribute to TD, many of which are often changing or are not easily recorded or publicly available. Some information may be available at the census geography level, but rarely at a household scale. Some cities have attempted to utilize evacuation assistance registries, yet these are typically incomplete, due to a lack of communication, a reluctance to sign up, as well as a high cost to maintain (Turner et al. 2010, 161). Other cities have attempted to conduct surveys or studies to better understand their TD populations, or partnered with local faith-based or community outreach programs in an effort to reach these members of the population (USGAO 2006, 27).

Researchers have used a variety of mapping techniques to attempt to pinpoint these populations spatially. Shay et al. utilized a choropleth technique, which overlaid six indicators of TD at the smallest geographic unit available, all dichotomized into values of 0 or 1 based on defined thresholds of disadvantage (Shay et al. 2016). Pulcinella et al. compared census-geography demographics with elevation, flood hazard, storm surge, and transit layers to assess flood vulnerability (Pulcinella et al. 2019). In other studies, a dasymetric mapping model has been used to more accurately represent the locations of residents within census geographies (Bian and Wilmot 2017; Wein et al. 2016).

The dasymetric technique is meant to address a common geospatial issue referred to as the Modifiable Areal Unit Problem (MAUP). In the simplest sense, the MAUP is defined as “the sensitivity of analytical results to the definition of units for which data are collected” (Fotheringham and Wong 1991, 1025). In geospatial analysis, this pertains to the fact that boundaries are often drawn arbitrarily, for either administrative or analytical purposes, and therefore, can skew analytical results. More specifically the MAUP includes both a scale and a zoning effect. The scale effect refers to the issue of aggregating the attributes of smaller areal units into larger areal units, which often leads to results that exclude outliers that may exist. The zoning effect refers to the statistical errors that can occur when areal units are applied to areas with strong positive spatial autocorrelation (Fotheringham and Rogerson 2008, 105-114; Jelinski and Wu 1996, 129).

Dasymetric techniques utilize additional layers, such as land use or parcel data, to disaggregate census-level data to smaller, more accurate areal units. What this accomplishes is that it adjusts the “denominator” to better represent rates of specific attributes (Maantay, Maroko, and Herrmann 2007, 77). Dasymetric methods vary, with some simply removing known non-residential areas from the analysis (such as open space or industrial sites), some using land use raster datasets as a proxy for population density, and others using cadastral (parcel) datasets (Wein et al. 2016; Bian and Wilmot 2017; Nelson, Abkowitz, and Camp 2015; Maantay, Maroko, and Herrmann 2007). All methods require some areal interpolation to redistribute population to new spatial units. If necessary, weighting or class schemes can be used to further control distribution and pre-processing steps can be undertaken to better represent group living situations, such as college dormitories, nursing homes, or military units (Maantay, Maroko, and Herrmann 2007; Strode, Mesev, and Maantay 2018). One method of note is the Cadastral-Based Expert Dasymetric System, in which residential area and/or residential units, gleaned from parcel data, are used as proxies to determine population distribution on a unit-by-unit basis (Maantay, Maroko, and Herrmann 2007).

Similar mapping techniques have been used to analyze social vulnerability. Many of these methodologies have remained at the granularity of census geographies assuming that population is uniformly distributed across neighborhoods. However, some researchers have utilized dasymetric techniques at the tax parcel level to more accurately reflect the distribution of these populations (Nelson, Abkowitz, and Camp 2015). Nelson et al. found that using census geographies can lead to underestimating the proportion of the population that is highly vulnerable by a factor of 7.5 times in some cases (Nelson, Abkowitz, and Camp 2015, 93).

The other major challenges of emergency planning for TD populations include attending to their vast diversity of needs. Often, members of these populations require specific medical or mobility assistance, making planning for their evacuation difficult. For example, evacuation vehicles must be equipped with wheelchair accessibility. If power outages occur, members of these populations may not be able to access elevators or their electronic wheelchairs may run out of battery (Renne et al. 2009, 42). Communicating with TD populations can be a major challenge due to a range of English proficiency and language levels. Major communication barriers include low-literacy, distrust in government, the use of jargon or complex language, or the use of inaccessible mediums (television, internet, etc.) (Turner et al. 2010, 163).

If it is possible to identify, plan for, and communicate with TD populations, it is still challenging to arrange for their transport. There are legal barriers to contracting with transit agencies or fleet operators as they can be wary of taking on liability (Renne et al. 2009, 41). There are also social barriers, as these populations may not wish to evacuate at all. As Renne et al. put it, there is the dilemma between the option to “remain in place hoping that the ensuing disaster will not render an intractable environment or heed the advice of authorities and evacuate with little guarantee that their medical condition will be properly tended to” (Renne et al. 2009, 37). Lastly, economic barriers may prevent these populations from evacuating as they may not be able to afford gas or a hotel room.

The Relevance of TD Populations Today

The challenges listed above demonstrate there is a great need to proactively plan for evacuating TD populations in the United States. The effects of global climate change are already being felt, often in the form of more frequent and more intense extreme weather events. In addition, an aging population and outdated infrastructure may contribute to an increase in vulnerable populations. Furthermore, the failure of governments to adequately plan for evacuating TD populations could be in violation of civil rights statutes (Martin 2015, 54). These combined factors ensure that planning for TD populations will be a focus for the foreseeable future.

3. Methodology

To determine where transportation disadvantaged (TD) populations are located with respect to extreme weather risk in the Boston metropolitan area, I began with the literature search and review presented in Chapter 2. The literature search focused on peer-reviewed, government, and grey literature on the topics of TD, evacuation planning, population mapping, climate justice, and the intersection of these areas. As the mapping methodologies became clearer, I performed more targeted searches in an effort to find literature on specific mapping techniques and tools.

Past research on mapping vulnerability and population distribution suggested that three methods are commonly used, each with an increasing level of granularity. The first method utilizes a standard choropleth mapping technique, in which TD is represented thematically via shading across census block groups. The second method employs the Intelligent Dasymetric Mapping (IDM) Toolbox published by the Environmental Protection Agency (EPA) to remove non-residential areas and to disaggregate census-level population to smaller and more accurate spatial units. The third and final method utilizes the Cadastral-Based Expert Dasymetric System (CEDS), which uses parcel data as a proxy for population distribution (Maantay, Maroko, and Herrmann 2007).

Mapping was performed primarily using ArcMap Version 10.7.1, with additional assistance from Microsoft Excel and Geoda software. The study area included the 97 cities and towns under the Boston Regional Metropolitan

Planning Organization (MPO), representing a total of 2,502 block groups (see Figure 1). 2010 Census Block group and town geographies were sourced from MassGIS, the state of Massachusett's Bureau of Geographic Information. Demographic and socioeconomic data was sourced from the 2010 Census and 2017 American Community Survey 5-year estimates. Based on the reviewed literature, I selected seven vulnerability attributes to represent levels of TD (see Table 1).

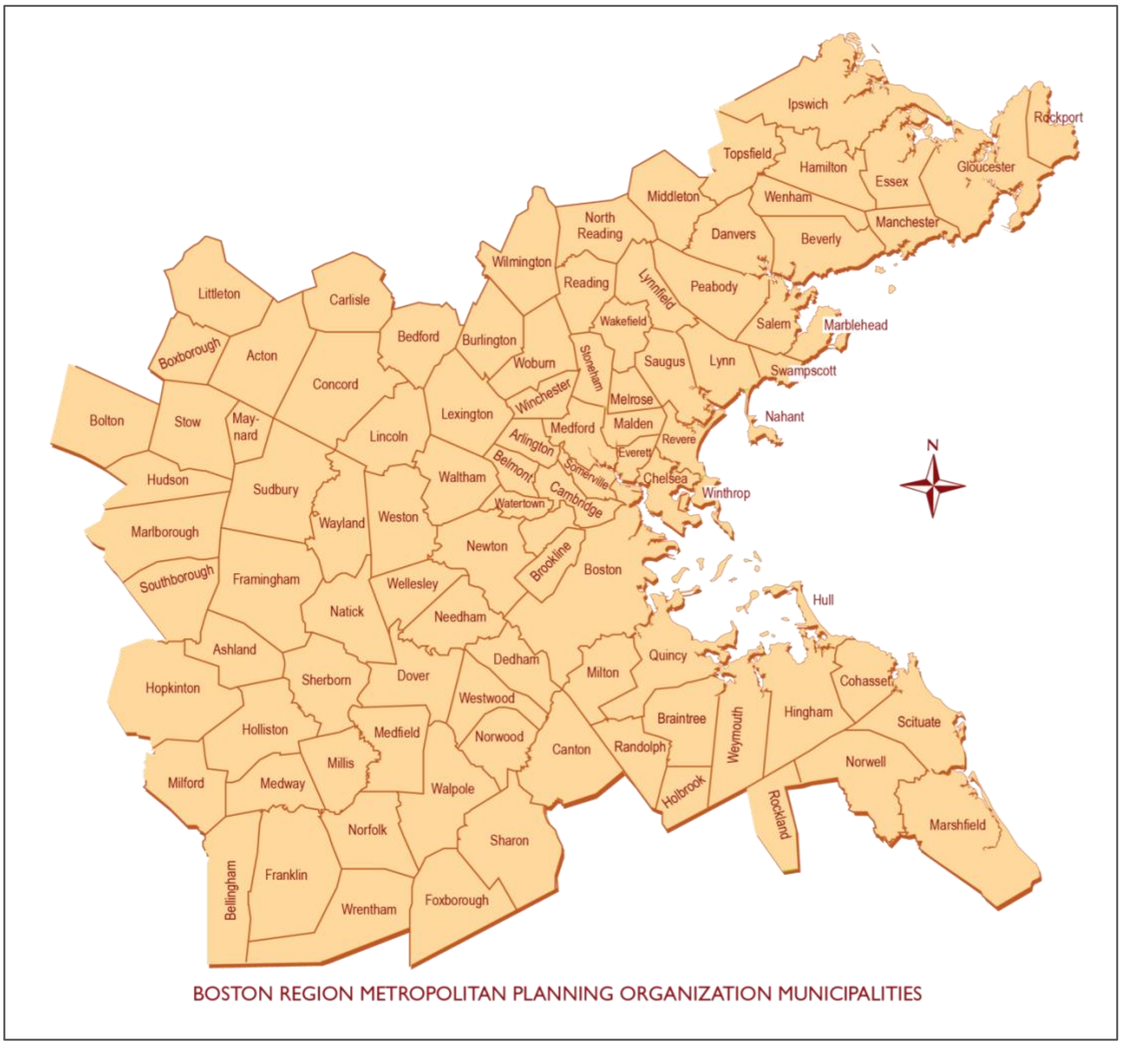

Figure 1. Boston MPO Towns and Cities (source: Boston MPO)

Table 1. Vulnerability Attributes

Attribute	Census Level	Description
Children	Block Group	% of population 18 and below
Elderly	Block Group	% of population 65 and above
Poverty	Block Group	% of population with income/poverty ratio below 1.49
Vehicle Access	Block Group	% of households with no vehicle available
Disability	Census Tract	% of population with disability
Language	Block Group	% of population that only speak English
Race	Block Group	% of population white

For the first two methods, the level of TD was determined using a binary system, in which each vulnerability attribute was coded as 0 or 1 for each block group, based on a pre-determined threshold. The threshold was designated as two standard deviations from the state mean (modeled after research by Shay et al. 2016). The mean values were calculated using the summary statistics tool in ArcMap and are shown below in Table 2.

Table 2. Binary Thresholds for Vulnerability Attributes

Variable	State Mean	State Std. Dev.	Threshold	Above/Below
Children	0.19646	0.08385	0.36416	above
Elderly	0.16156	0.09576	0.35309	above
Poverty	0.11974	0.11732	0.35438	above
Vehicle Access	0.12367	0.15253	0.42874	above
Disability	0.11987	0.05007	0.22000	above
Language	0.74201	0.20644	0.32914	below
Race	0.78549	0.22158	0.34232	below

Once thresholds were determined for each vulnerability attribute and the coding was complete, a total level of TD was calculated for each block group by summing the binary codes. Therefore, the range of possible total TD for each block group was between 0 and 7. The highest TD value assigned to any block group was 5 and the mean TD level for the study area was 2.8.

Choropleth Method

The choropleth method visualized block groups thematically by their total level of TD. Block groups with darker colors exceeded the threshold of several vulnerability attributes while lighter block groups met fewer thresholds. In this method, population was assumed to be uniform across the census geographies and potential multicollinearity was ignored; therefore, this produced the coarsest set of results.

Intelligent Dasymetric Mapping

The second method utilized the EPA IDM Toolbox to more accurately distribute residential population within block groups. This tool takes input census-level population data along with an ancillary land-use data set to produce "a floating point output raster of revised population density" (US EPA 2017). By designating uninhabited land and a coverage percentage, representing an estimation of how much the population covers the census geography, the output more accurately reflects the location of people within the census geography. I used the default coverage percentage of 80%. I used the 2016 National Land Cover Database (NLCD) raster layer as an ancillary land-use data set. The NLCD is sourced from the Multi-Resolution Land Characteristics Consortium and includes 20 different land use designations at a resolution of 30 x 30 meters (MRLC, n.d.). Prior to running the tool, I reclassified the NLCD into four categories based on the density of development (see Table *3*). In addition, I reclassified any pixels falling within official open space (per MassGIS) as uninhabited.

Table 3. Reclassified NLCD Land Cover Values

NLCD Land Cover Designation	Reclassified Value
Unclassified	Uninhabited
Open Water	Uninhabited
Developed, Open Space	Non-urban inhabited
Developed, Low Intensity	Low-density residential
Developed, Medium Intensity	High-density residential
Developed, High Intensity	High-density residential
Barren Land	Uninhabited
Deciduous Forest	Uninhabited
Evergreen Forest	Uninhabited
Mixed Forest	Uninhabited
Shrub/Scrub	Uninhabited
Herbaceous	Uninhabited
Hay/Pasture	Uninhabited
Cultivated Crops	Uninhabited
Woody Wetlands	Uninhabited
Emergent Herbaceous Wetlands	Uninhabited

The output of the tool was a raster layer with new population counts and densities for each block group. Each pixel was associated with a collection of other pixels within the same block group, assigned a “new population” based on the land use class of those pixels. A “new density” field represented the approximate population per pixel. This raster layer was converted to a series of point layers each representing a different attribute; then these point layers were joined together to create a single point layer. Each point represented a single pixel, its associated population attributes, and total TD (based on the previous binary system). To avoid rounding errors, I recalculated the “new density” for each point based on the “new population” and “count” fields.

Cadastral-Based Expert Dasymetric System

The third and final method utilized parcel-level data for the study area to dasymetrically redistribute block group population. 2019 state-level parcel data, which does not include the City of Boston, was sourced from MassGIS; 2016 City of Boston parcel data was sourced from Analyze Boston. To prepare the data, I isolated residential parcels using the Property Type Classification Codes from the Massachusetts Department of Revenue (for the state-level parcel data) and the Massachusetts Property Classification System Occupancy Codes (for the Boston parcel data). Parcels coded as mixed-use were included as "residential" if they were labeled as primarily residential. To supplement the data supplied within these two parcel layers, I joined a 2019 Metro Boston Region Massachusetts Land Parcel Database layer prepared by the Massachusetts Area Planning Council (MAPC), which included a better estimate of units within each parcel.

Following the CEDS system, I then calculated residential area (RA) and residential unit (RU) values for each parcel. The variables used for each are listed in Table 4. In the few cases in which RA was zero and RU was *not* zero, I calculated an adjusted residential area (ARA) using the formula below. Note that in both parcel layers I did not have access to total number of units, so the formula simply added any building area to residential area.

$$\begin{gathered} ARA = M \times (BA \times RU \div TU) + RA \\ \boldsymbol{IF}\ RA = 0\ \boldsymbol{AND}\ RU > 0, \boldsymbol{THEN}\ M = 1, \boldsymbol{ELSE}\ M = 0 \end{gathered} \tag{1}$$

where:

ARA = adjusted residential area within parcel;
BA = building area (residential and commercial);
RU = number of residential units;
TU = total number of units (residential and commercial);
RA = residential area within parcel; and
M = Binary variable designating ancillary data for ARA.

Table 4. Residential Area and Residential Unit Variables

Data Set	RA	Description	RU	Description
State Parcels	RES_AREA	Applies primarily to 1, 2 & 3 family dwellings based on exterior building measurements or residential condominiums based on deeded unit areas. Building area may be recorded as gross square-feet, adjusted gross square-feet, or finished area. Basement area may or may not be included in finished area. Partial story-heights and attic areas may be treated differently by different CAMA systems. Gross area may include non-living areas such as porches and decks or attached garages	Units_est (where available) or UNITS	MAPC's best estimate of number of units, based on comparing the reported units, count of assessors records, and reported classification code; Number of living/dwelling units, and also other units, for example, commercial condos and storage units in a warehouse
Boston Parcels	LIVING_AREA	Total living area for residential properties	Units_est	MAPC's best estimate of number of units, based on comparing the reported units, count of assessors records, and reported classification code

Source: MassGIS, Analyze Boston, MAPC

Upon calculating these proxies, I merged the two parcel layers to generate one parcel layer for the MPO study area. Using this layer, I aggregated total RU and ARA at both the census block group and tract levels. These sums were then joined back to the parcel level so each parcel was associated with its own RU and ARA as well as the aggregated values of the census tracts and blocks in which it resided.

Dasymetric populations were calculated by multiplying the census population with the ratio of proxy units (RU or ARA) in the formula below. This process generated four population values for each parcel: block group RU, block group ARA, tract RU, and tract ARA.

$$POP_p = POP_c \times \frac{U_p}{U_c} \tag{2}$$

where:

POP_p = dasymetrically derived parcel-level population;
POP_c = census population;
U_p = the number of proxy units at the parcel level (RU or ARA); and
U_c = the number of proxy units at the census block group or tract level (RU or ARA per block group or tract).

Following these calculations, both the tract RU and tract ARA were aggregated to the block group level, representing two estimations of total block group population. The following formula was used to calculate the population difference between these estimations and the actual block group population reported by the census.

$$POP_{diff} = |POP_{BG} - POP_{est}| \tag{3}$$

where:

POP_{diff} = the difference between census and estimated populations per block group;
POP_{BG} = census block group population; and
POP_{est} = estimated population (RU or ARA) derived from the census tract.

Finally, the expert system utilized the following rule to determine which proxy unit best disaggregated the population for each block group (which of RU and ARA produced the smaller POP_{diff} value). This process resulted in a per-parcel population for each residential parcel in the study area.

$$\boldsymbol{IF}\ RU_{POP_{diff}} \leq ARA_{POP_{diff}}\ \boldsymbol{THEN}\ POP_p = POP_{RU\_BG} \quad (4)$$
$$\boldsymbol{ELSE}\ POP_p = POP_{ARA\_BG}$$

where:

RU_POP_{diff} = the absolute difference between the census block group population and the estimated block group population derived from the census tract population based upon number of residential units;
ARA_POP_{diff} = the absolute difference between the census block group population and the estimated block group population derived from the census tract population based upon residential area;
POP_p = the final estimated tax lot population dasymetrically derived from the census tract population based on the best performing proxy unit;
POP_{RU_BG} = the estimated parcel population dasymetrically derived from the census block group population based on number of residential units; and
POP_{ARA_BG} = the estimated parcel population dasymetrically derived from the census block group population based on the adjusted residential area.

I performed a principal component analysis (PCA) using the singular value decomposition method in the analysis software Geoda to better represent levels of TD with the CEDS results. This process reduces dimensionality by accounting for the correlation between many of the vulnerability attributes identified in the literature, "rotate(s) the multidimensional variables into a new group of mutually orthogonal vectors," and produces a series of principal components representing common profiles in the data (Xiao, Wang, and Wang 2018, 34). By pairing the new spatial representation of population distribution, based on the CEDS system, with a profile that best represented TD, based on the PCA, I produced my third and final map, showing the distribution of TD in the Boston metropolitan area at the finest scale I could produce. Using the results of the CEDS analysis, I also produced a cluster analysis of TD using the Local Moran's I function in ArcMap.

The results from the three different methodologies used spatial data at three different scales to estimate population. The first estimated population based on standard census-geographies, the second based on pixels of differing land use, and the third based on residential parcels. In the next section, I assess the relationship between TD populations and extreme weather risk.

Walkshed Analysis

First, I assessed access to emergency shelters. Unfortunately, the state of Massachusetts does not publish an official list of emergency shelters; therefore, I assumed all public schools (excluding private, charter, special education, and vocational) outside of evacuation zones could be used as emergency shelters. To assess access, I estimated the TD population located within 10, 15, and 20-minute walks of the shelters. I built a model using Network Analysis in ArcMap to produce three service areas, or "walksheds," around each school. The distances were based on walking speeds published in the *Transportation Research Record* (Fitzpatrick, Brewer, and Turner 2006, 21). This report makes the following recommendation: "3.5-ft/s (1.07-m/s) walking speed for timing of a traffic signal; if older pedestrians are a concern, then a 3.0-ft/s (0.9-m/s) walking speed should be used" (Fitzpatrick, Brewer, and Turner 2006, 21). Since this analysis is concerned with TD populations, who may very well be elderly or otherwise mobility impaired, I used the suggested speed of 0.9 m/s, resulting in walksheds of 540, 810, and 1,080 meters.

After producing the three service areas, I built a series of models in ArcMap using modelbuilder which calculated the population residing within each walkshed and the proportion of said population that could be considered TD. An example of this model is displayed in Figure 2. For the Choropleth map, this was accomplished by rasterizing the block group polygon layers and summing the population density of pixels within each walkshed. The IDM raster was similarly summed. To calculate the walkshed population produced using the CEDS system, I summed the populations of parcels intersecting each walkshed. For the Choropleth and IDM methods, total TD levels greater than or equal to three were considered TD. For the CEDS methods, TD was represented as a standard deviation greater than or equal to two from the mean value of the first principal component.

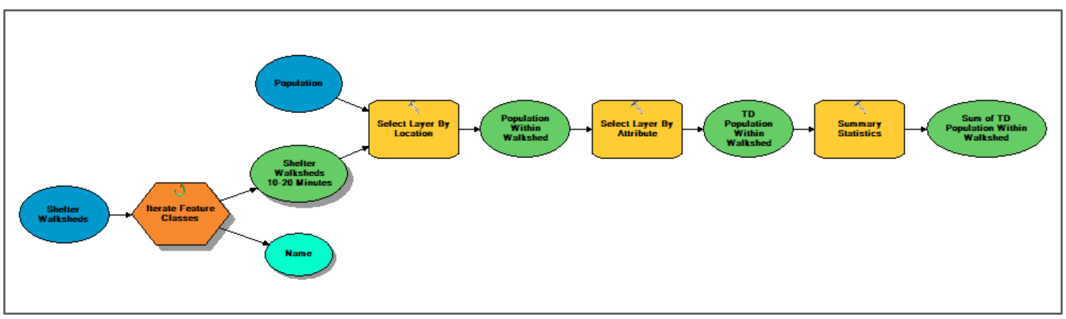

Figure 2. Walkshed Population Model

Evacuation Zone Analysis

I created another model in ArcMap to calculate the total population and TD population residing within each official hurricane evacuation zone. Hurricane evacuation zone layers for each relevant MA county (as of May 2016) were obtained from the US Army Corps of Engineers, New England District. Evacuation zones are based off the predicted inundation and storm surge impact. These were merged to create an evacuation zone layer, coded for zones A, B, and C. Note that zone C has been designated by just Boston and Cambridge as a potential flood zone "depending on the track and intensity of the storm" (Mass.gov 2020b).

Interview Identification

After completing the mapping, I identified several neighborhoods within the study area having a combination of high levels of TD, high risk of flooding, and poor walking access to shelters. Within these neighborhoods, I identified several community organizations that had a close connection with the residents. The community organizations selected for interviews represented a wide range of advocacy initiatives including public health, affordable housing, senior care, disability rights, and racial equity. In addition, I identified several state-level agencies and organizations in the realm of emergency and evacuation planning. I conducted semi-structured interviews with representatives from these organizations. I solicited and conducted these interviews in partnership with Melanie Gárate, the Climate Resiliency Project Manager at the Mystic River Watershed Association based in Arlington, MA. Melanie's deep knowledge of the watershed and the many nearby communities and organizations was valuable to the mission of this thesis.

The goal of the interviews was two-fold. First, I aimed to ground truth the mapping results and understand the accuracy of the methodologies I pursued. Second, I aimed to understand the community's evacuation resources, if any, and how community leaders consider TD in their work. Therefore, I shared and discussed the mapping results with each interviewee and asked them to assess the accuracy of locations of high TD based on their local knowledge. I prepared an interactive version of the CEDS map using the online mapping software CARTO so that interviewees could interact with and move around the focus area of the dataset (see Appendix A for more information). I also spoke with interviewees about their definitions and understanding of TD, their experience and knowledge of evacuation planning resources in their communities, and the best ways in which to help TD populations before, during, and after extreme weather events requiring evacuation. A full list of interview questions is included in Appendix B.

CONCLUSION

In Chapter 4 and Chapter 5, I will present the results of the three mapping methods, the walkshed and evacuation zone analyses, and the results of the qualitative interviews. In addition, I will compare the population estimates resulting from each of the methods and display their trends graphically.

4. Mapping Results

The three mapping methods produced slightly different pictures of the Boston metropolitan study area; however, the differences in the underlying population data were more stark. The Choropleth method was coarser than the Intelligent Dasymetric Mapping (IDM) Method, which in turn, was coarser than the Cadastral-Based Expert Dasymetric System (CEDS) method in its estimation of population distribution. This is evident in comparing Figure 3 to Figure 5, which shows a clearer demarcation of open space and developed land. Figure 7, which displays the CEDS results, only shows transportation disadvantage (TD) for residential parcels, which have been assigned populations on a per-parcel basis. This progression in granularity reveals the potential for misrepresenting TD populations in areas of high risk.

This chapter will discuss the results of each method, compare their population estimations, and estimate where TD is clustered in the study area. A discussion of these results will follow in Chapter 6.

Choropleth Results

The results of the Choropleth method, which utilizes a binary system to determine levels of TD and a thematic shading symbology, are shown in Figure 3. This method assumes uniform population distribution across census block groups and classifies each block group based on its total level of TD, or how many vulnerability attributes have exceeded the threshold in that block group. Figure 3 shows high values of TD in the Chelsea, Dorchester, East Boston, Framingham, Lynn, Revere, Randolph, and Roxbury areas. The size of block groups varies based on population, as the map suggests, so there is more variation in levels of TD closer to the city of Boston, where block groups are smaller. A closer look near Boston can be seen in Figure 4. This map suggests that some neighborhoods, like Dorchester, have the highest levels of TD.

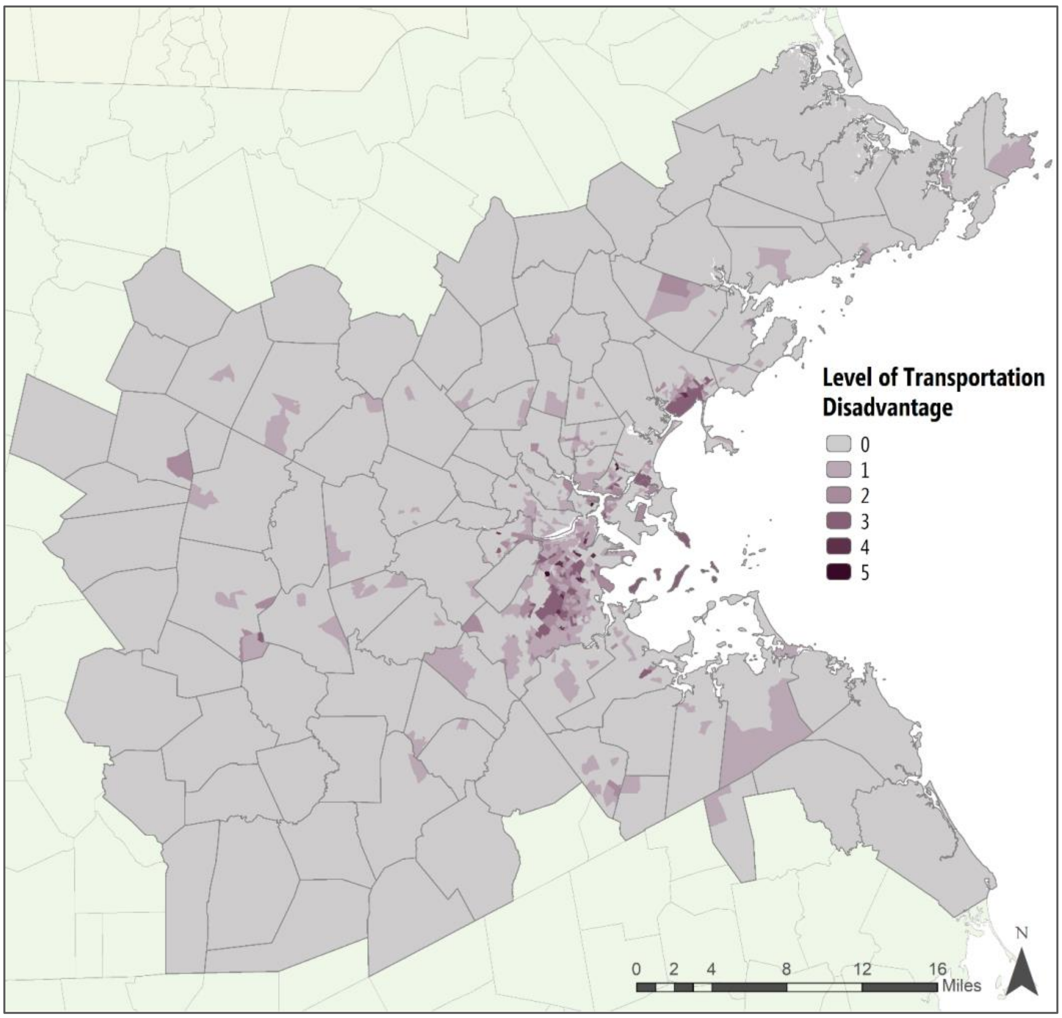

Figure 3. Choropleth Map of Transportation Disadvantage

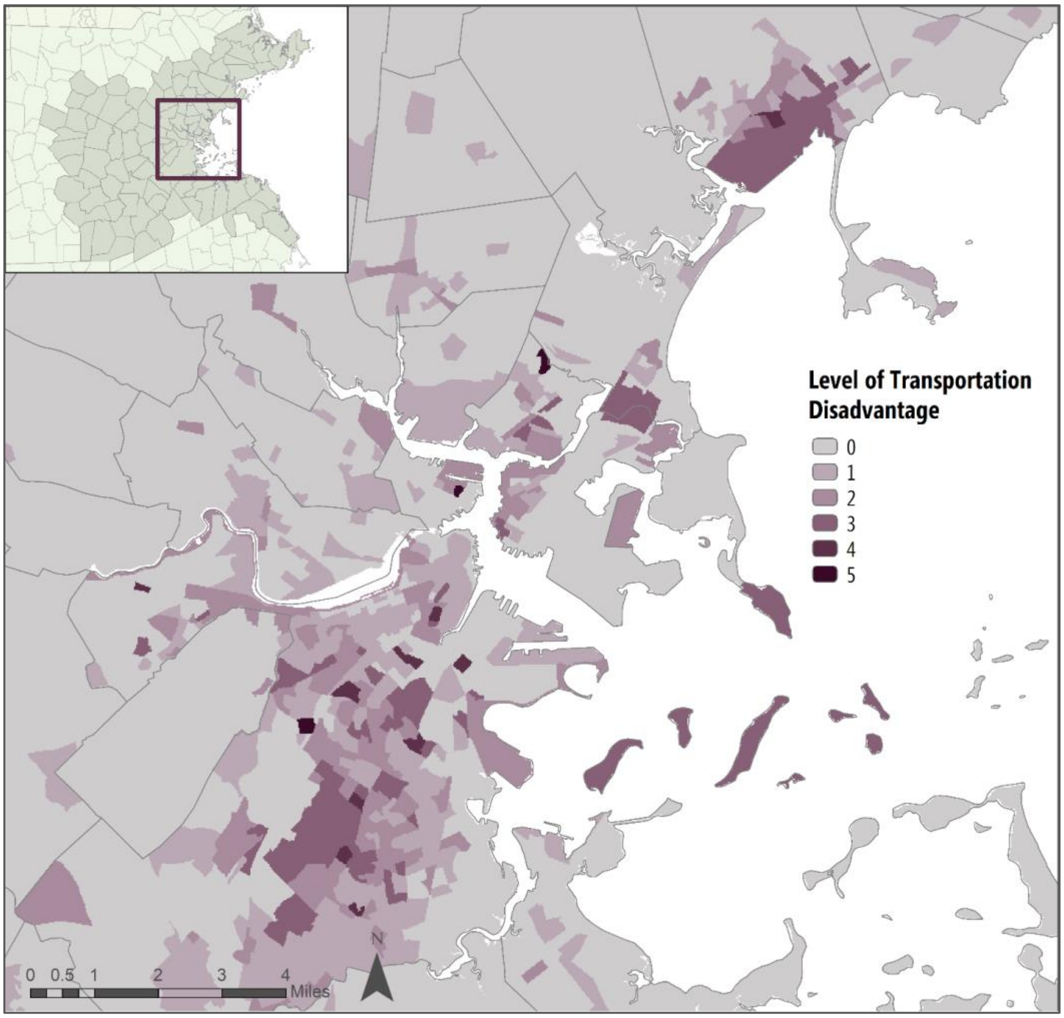

Figure 4. Choropleth Map of Transportation Disadvantage, Boston

Intelligent Dasymetric Mapping Results

The results of the IDM method, which utilizes the same binary system to determine levels of TD but a rasterized land use dataset to redistribute population, are shown in Figure 5. This method estimates population distribution based on density of land use instead of assuming uniform density across block groups. It excludes open space and uninhabited land uses, only showing population for areas in which people are likely to reside. Further, pixels representing higher density development are assigned higher population densities than pixels representing low density development. Therefore, the population estimates for TD populations are more accurate than the Choropleth method. The shading of TD resembles the Choropleth method but the removal of uninhabited pixels helps to better pinpoint the locations of TD populations. A closer look at Boston can be seen in Figure 6. This figure suggests the neighborhoods of Dorchester, Lynn, and Revere have high TD populations.

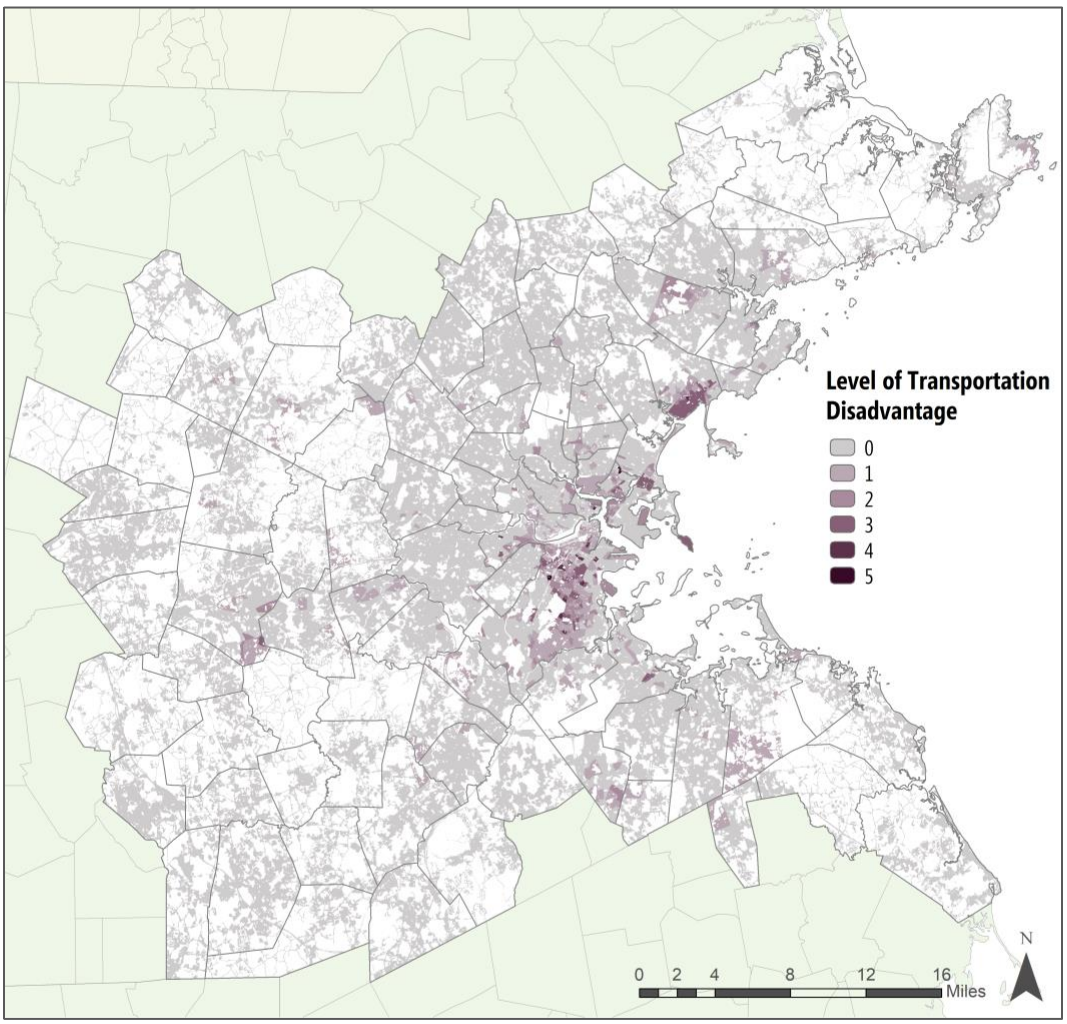

Figure 5. IDM Map of Transportation Disadvantage

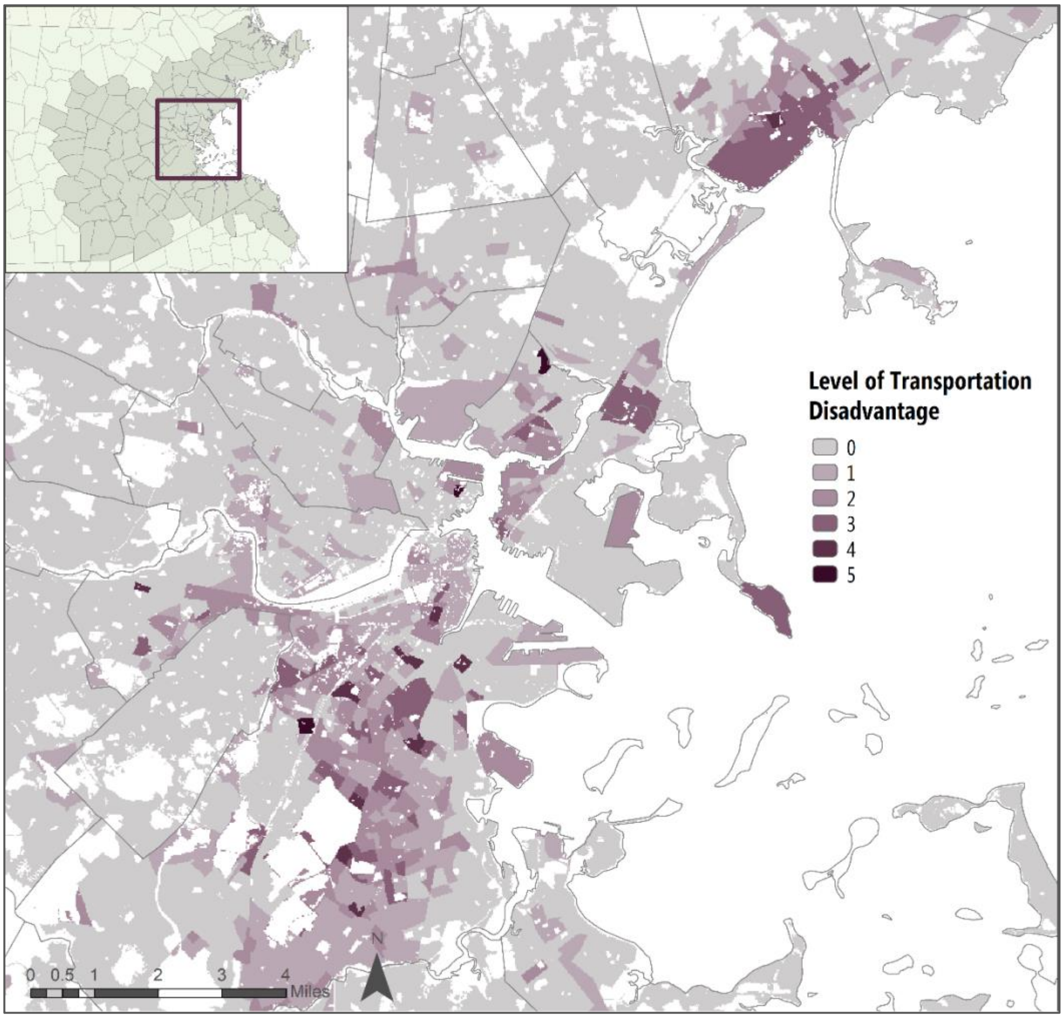

Figure 6. IDM Map of Transportation Disadvantage, Boston

CADASTRAL-BASED EXPERT DASYMETRIC SYSTEM RESULTS

The results of the CEDS method, which utilizes parcel data to redistribute population along with a principal component analysis (PCA) of the vulnerability attributes, are shown in Figure 7. The first principal component (PC1) was used as the TD score, as it most closely represented the attributes of TD populations and it explained the highest proportion of variance at a value of 0.41. The variable loadings of PC1 are shown in Table 5.

Table 5. Variable Loadings for Principal Component 1

Attribute	Description	Variable Loading
Children	% of population 18 and below	- 0.059
Elderly	% of population 65 and above	- 0.227
Poverty	% of population with income/poverty ratio below 1.49	0.473
Vehicle Access	% of households with no vehicle available	0.436
Disability	% of population with disability	0.270
Language	% of population that only speak English	- 0.465
Race	% of population white	- 0.492

This map assumes population distribution based on population proxies (residential units or residential area) and classifies each parcel based on the number of standard deviations from the mean of PC1. This method is even more fine grained in its ability to estimate where people live compared to the Choropleth and IDM methods. It excludes open space and non-residential parcels, only showing parcels where one can reasonably expect people to live. Parcels with more residential units or a higher residential area are assigned higher population values than parcels with fewer residential units or lower residential areas. In addition, this method utilizes a PCA which accounts for multicollinearity among the vulnerability attributes. As Figure 7 shows, this method is highly specific in locating parcels which are most likely to exhibit high vulnerability based on the TD profile estimated by the PCA. High levels of TD are found in the Allston, Chelsea, Dorchester, East Boston, Framingham, Lynn, Malden, Mattapan, Randolph, Revere, and Roxbury areas. A closer look at Boston can be seen in Figure 8, which shows that the neighborhoods of Dorchester, East Boston, and Lynn are most vulnerable.

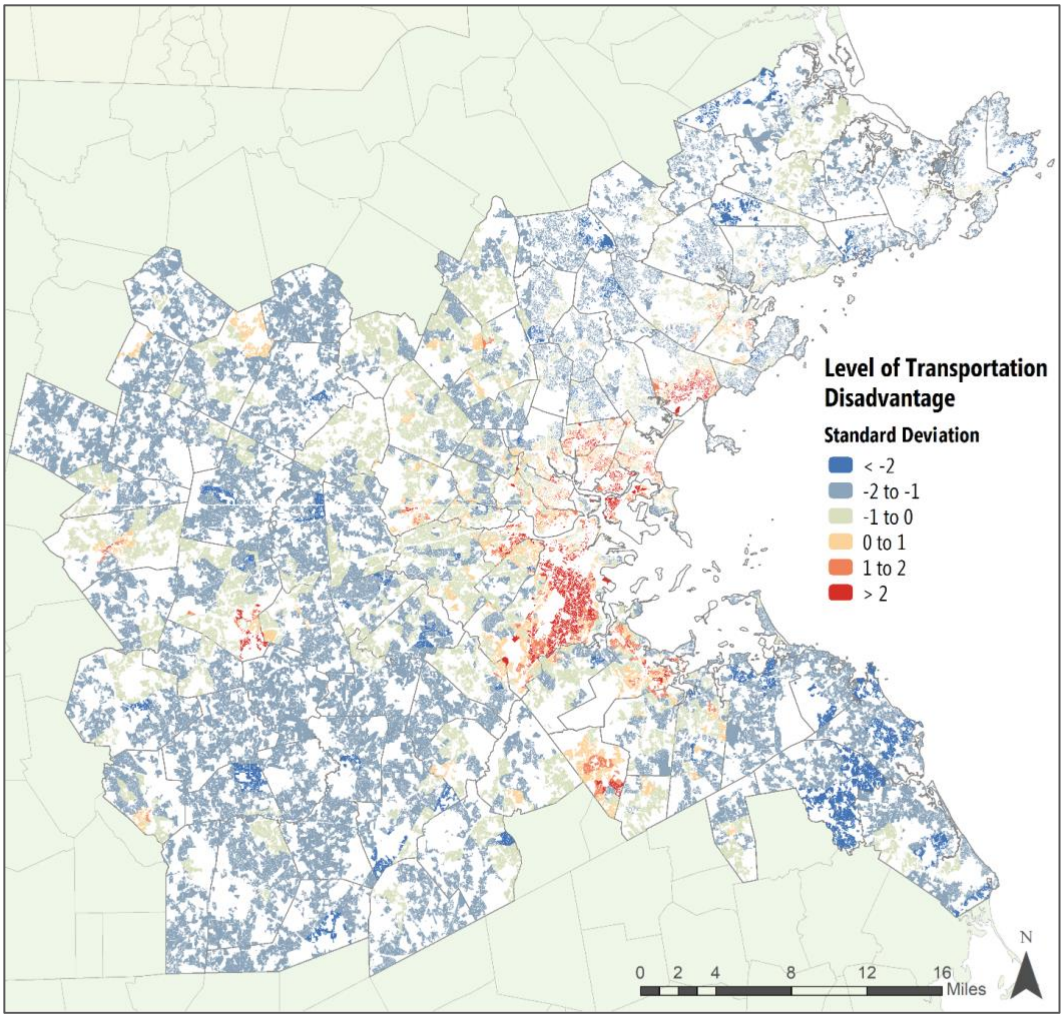

Figure 7. CEDS Map of Transportation Disadvantage

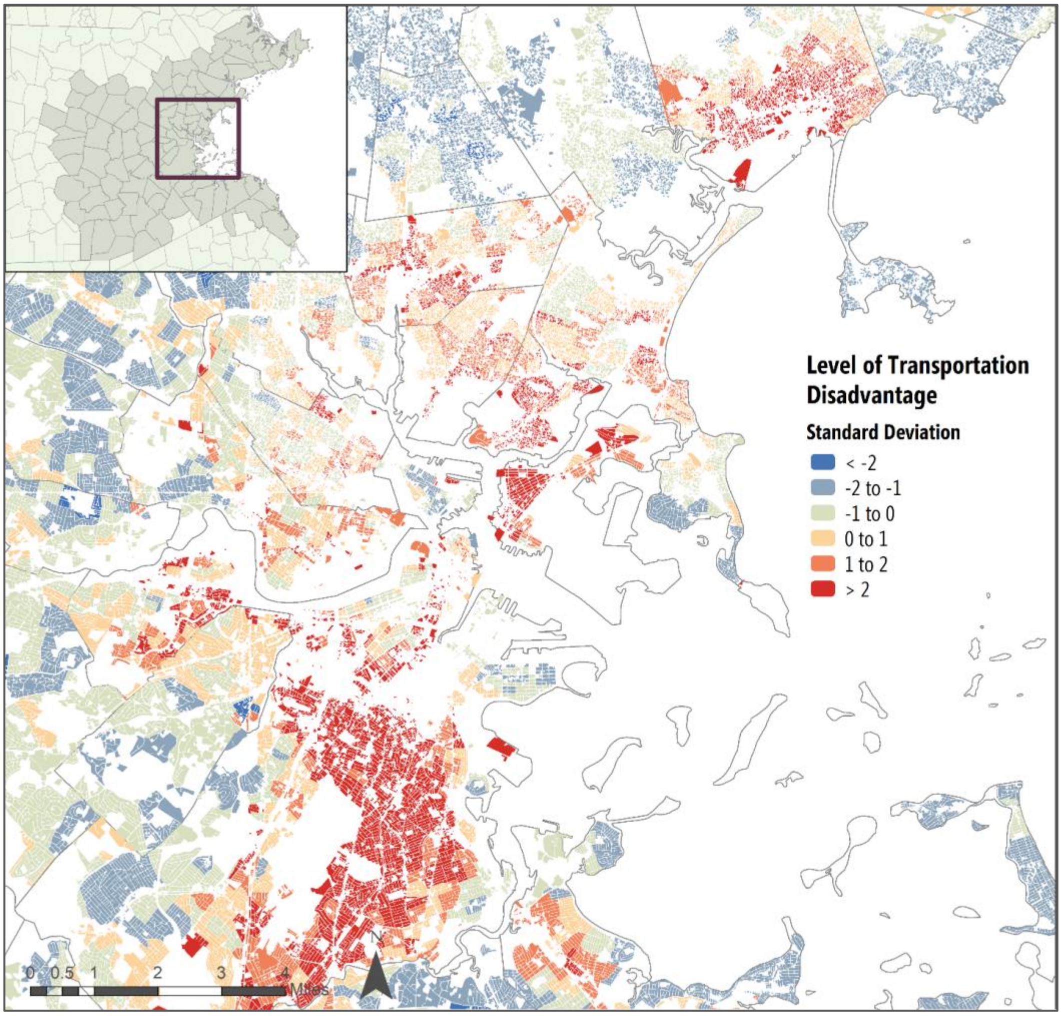

Figure 8. CEDS Map of Transportation Disadvantage, Boston

Cluster Analysis Using Local Moran's I

The results of the Local Moran's I function using the CEDS method are shown in Figure 9. This analysis reveals areas where high and low TD values are clustered (high surrounded by high or low surrounded by low) as well as outlying areas (high surrounded by low or low surrounded by high) (Griffin and Sener 2016, 135). Each cluster is significant ($p<0.05$) unless labeled as "Not Significant." This analysis reveals that much of Boston and the immediately surrounding cities are dominated by high-high clusters, while the towns farther from the city show mostly low-low clusters. Low-high outliers appear in several generally higher-income areas, such as the Back Bay, Brookline, and Cambridge while high-low outliers appear mostly outside of the metropolitan area, in areas such as Framingham, Lexington, and Weston. A closer look at Boston can be seen in Figure 10, which suggests that the majority of neighborhoods surrounding downtown Boston have significant numbers of high TD populations.

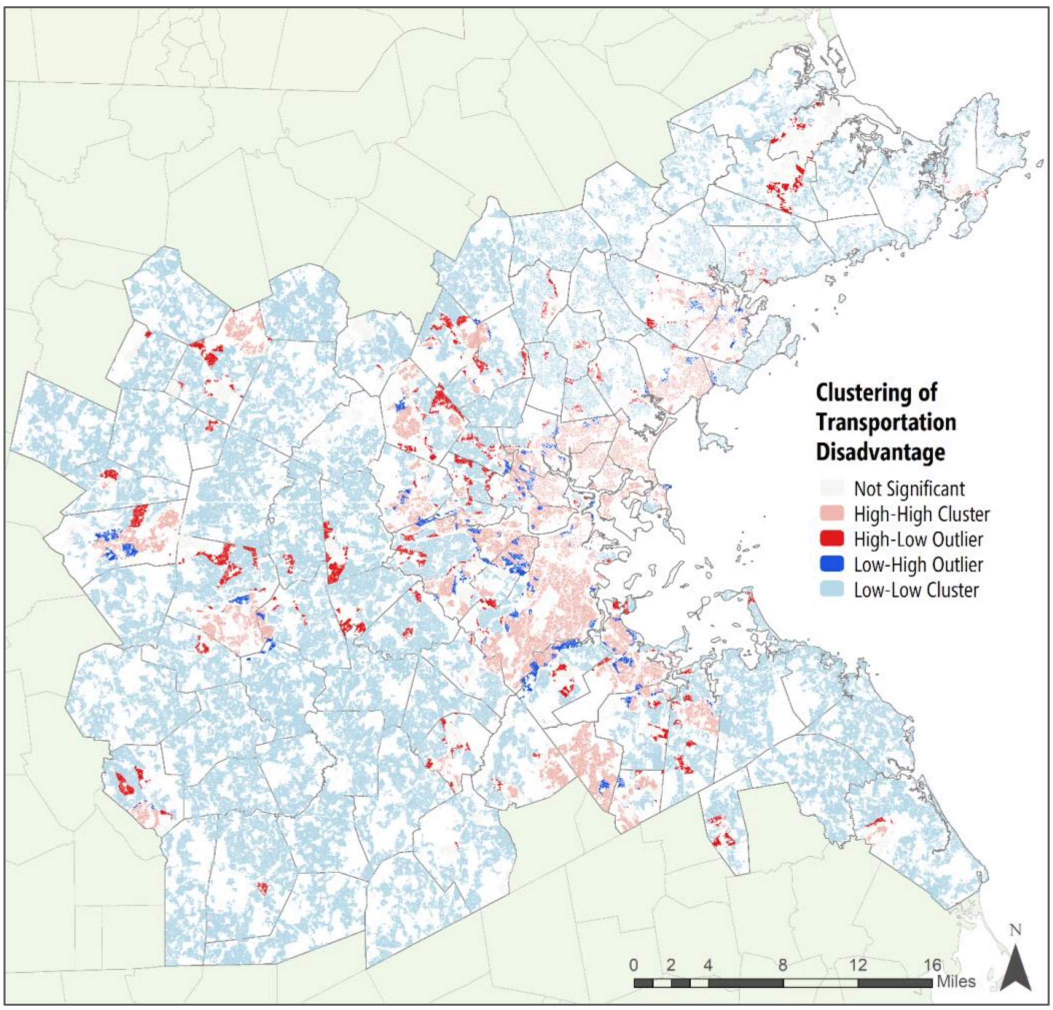

Figure 9. Cluster Analysis

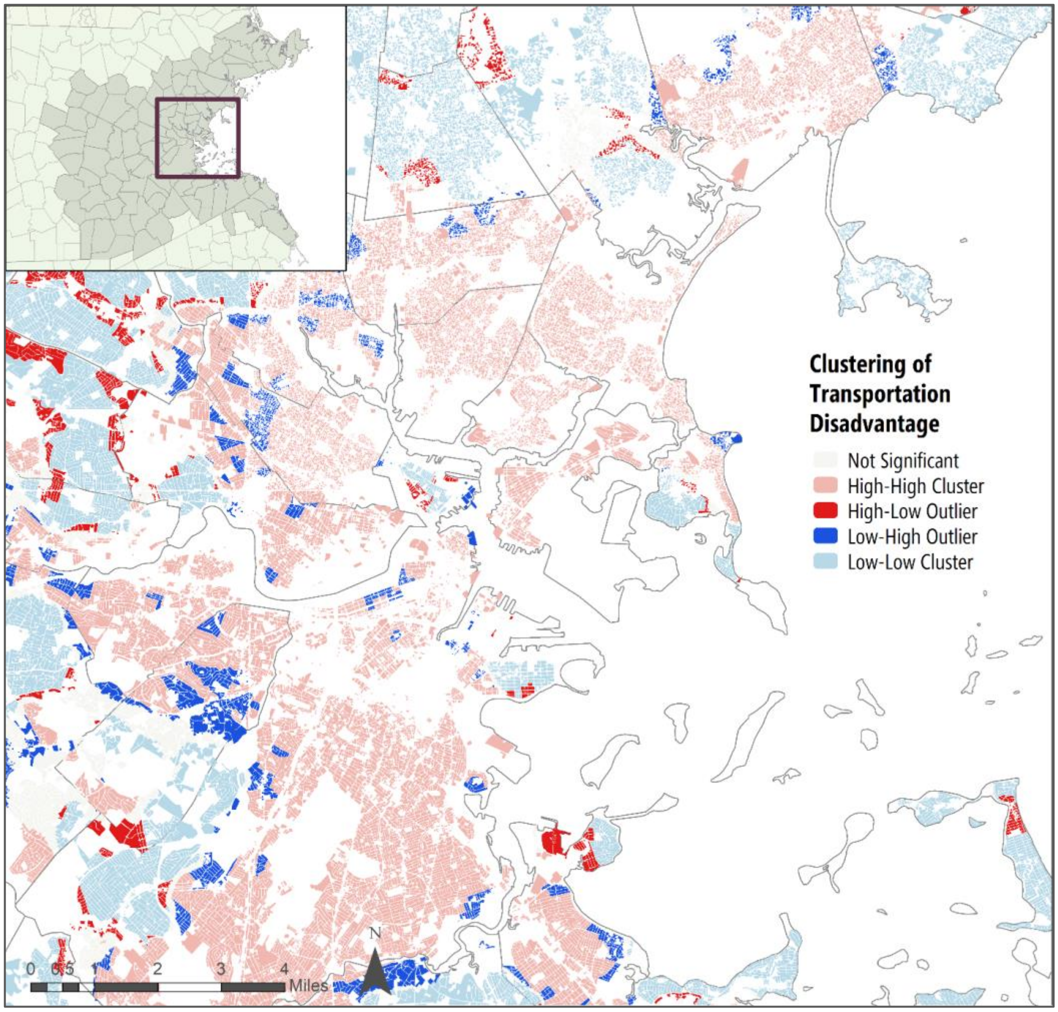

Figure 10. Cluster Analysis, Boston

Walkshed Analysis

The walkshed analysis was performed for the results from all three mapping methods. A map showing the IDM results with the 10, 15, and 20-minute walksheds from each shelter is shown in Figure 11. Note there are several areas of high TD (TD score greater than or equal to three) that are assumed to be farther than a 20-minute walk from a shelter. For simplicity, this analysis assumes schools located within evacuation zones are not used as shelters. In actuality, depending on the strength of a storm, shelters are likely used within evacuation zones.

As expected, the density of public schools increases closer to the city, where population density is highest and many walksheds overlap. In more suburban and rural areas, there are larger gaps between shelter walksheds. This analysis demonstrates the potential for overcrowding at shelters immediately outside of evacuation zones, which would have to absorb those evacuating from Boston.

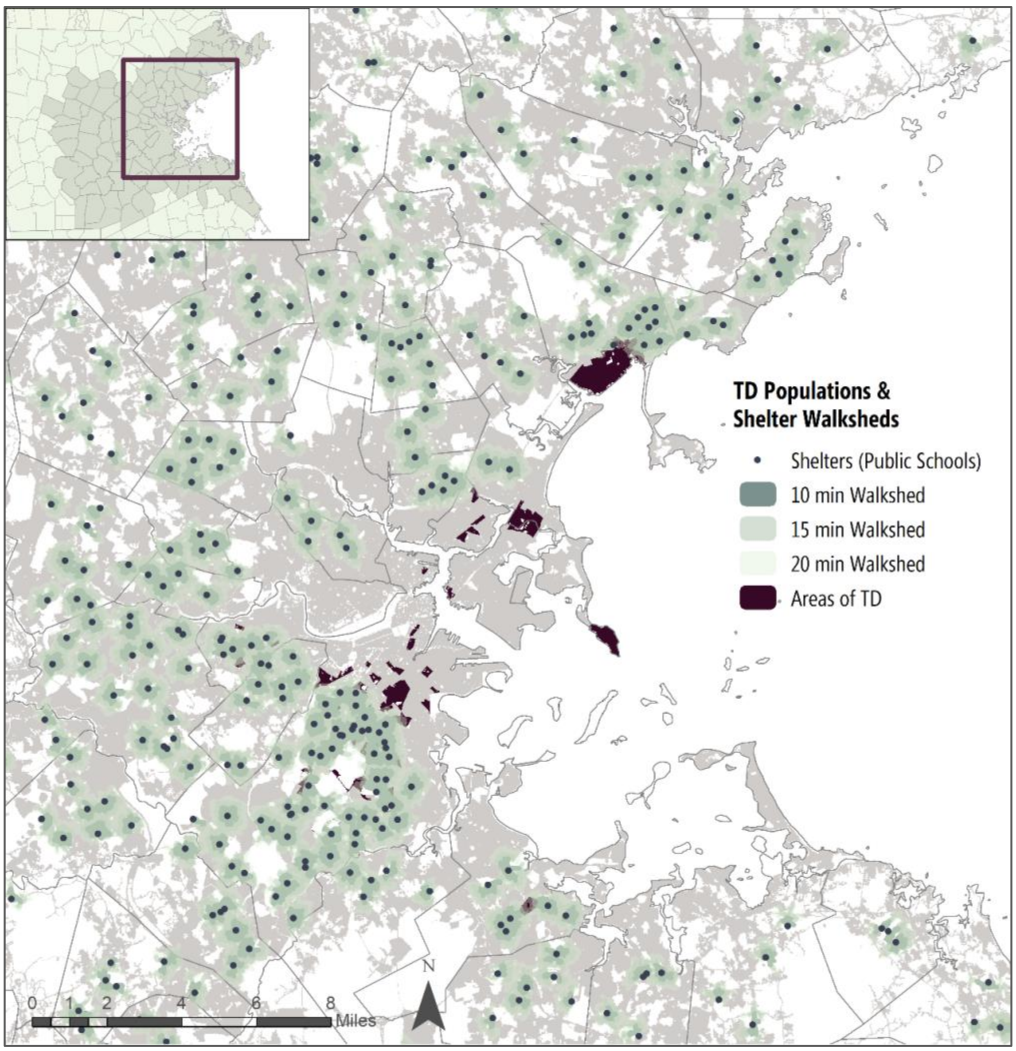

Figure 11. Shelter Walksheds

Evacuation Zone Analysis

The evacuation zone analysis was also performed for all three mapping methods. Figure 12 displays the IDM results along with evacuation zones A, B, and C. Zone A, where flooding is expected to occur first, covers the outermost coast north and south of Boston, as well as the areas bordering the Mystic River, extending up to Winchester. Zone B covers the greater part of Boston, East Boston, and Cambridge, as well as key areas along the coast and Mystic River. Lastly, zone C, which has been designated by Boston and Cambridge as a potential flood zone depending on the storm, extends across the neighborhoods of Beacon Hill, Back Bay, Allston, and parts of the South End and Dorchester. As seen on the map, several areas of high TD are located within these zones.

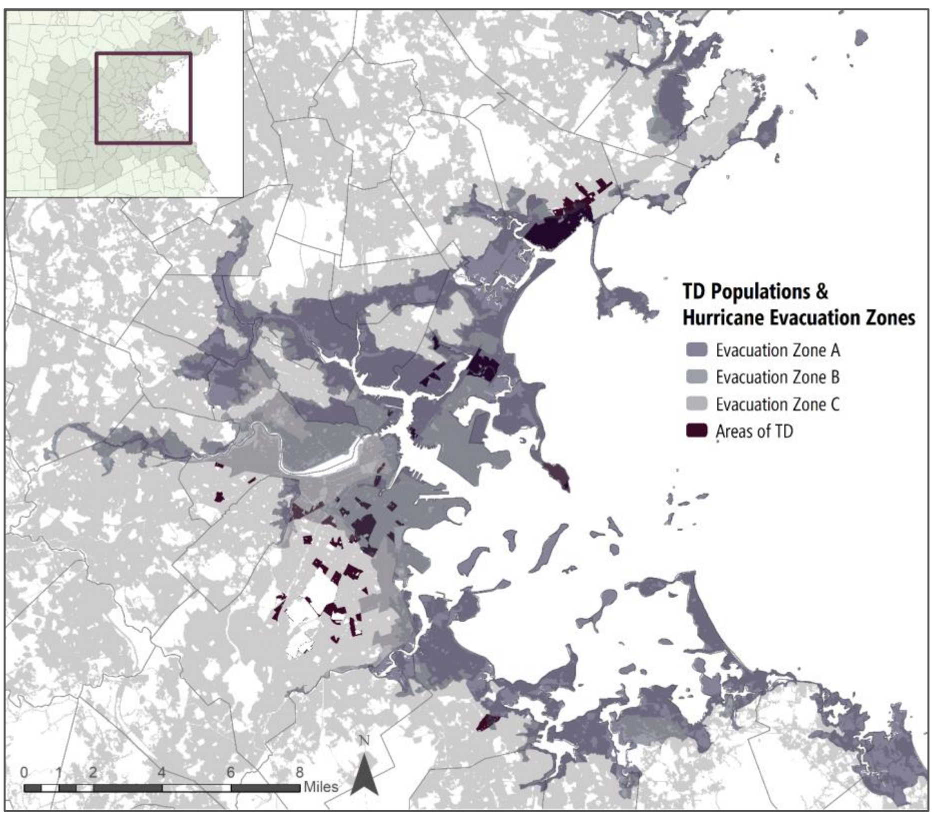

Figure 12. Hurricane Evacuation Zones

COMPARING METHODS

To better understand the differences in TD estimates among these methods, I compared the results of the walkshed and evacuation zone analyses. Table 6, Figure 13, and Figure 14 present these results.

Table 6. A Comparison of Population Estimates for Each Mapping Method

	Choropleth			IDM			CEDS		
Walkshed	TD	Total	% TD	TD	Total	% TD	TD	Total	% TD
10 min	24,308	497,257	4.9%	24,572	501,910	4.9%	146,975	621,489	23.6%
15 min	35,474	898,001	4.0%	37,706	938,725	4.0%	228,612	1,082,357	21.1%
20 min	45,736	1,260,544	3.6%	45,845	1,333,575	3.4%	281,914	1,489,633	18.9%
>20 min	36,893	2,126,058	1.7%	36,728	2,022,283	1.8%	91,833	1,599,992	5.7%
Evacuation Zone	TD	Total	% TD	TD	Total	% TD	TD	Total	% TD
A	13,062	397,486	3.3%	13,042	383,443	3.4%	88,616	393,226	22.5%
B	20,653	324,857	6.4%	19,908	317,686	6.3%	85,115	340,860	25.0%
C	7,177	173,935	4.1	7,573	176,988	4.3%	70,598	172,632	40.9%
Outside	41,737	2,490,364	1.7%	42,050	2,477,756	1.7%	253,679	2,462,873	10.3%
Total TD Population	82,629 (2.4% of total)			82,573 (2.5% of total)			487,389 (14.1% of total)		

Note: TD refers to a Total TD score of greater than or equal to 3 (for Choropleth and IDM methods) or a standard deviation of greater than or equal to 2 (for CEDS method).

Table 6 suggests that the results of the Choropleth and IDM analyses are very similar. Even with the reallocation of population based on land use, the IDM method does not alter the results significantly compared with the Choropleth method’s assumption of uniform population distribution. However, when compared with the results of the CEDS method, it appears both the Choropleth and IDM methods severely underestimate both total and TD population within these areas. For example, the CEDS method estimates 10% more total TD residents and 15% more TD residents living within evacuation zones than both the Choropleth and IDM methods. Figure 13 and Figure 14 show these results graphically, demonstrating the difference in total and TD population estimates.

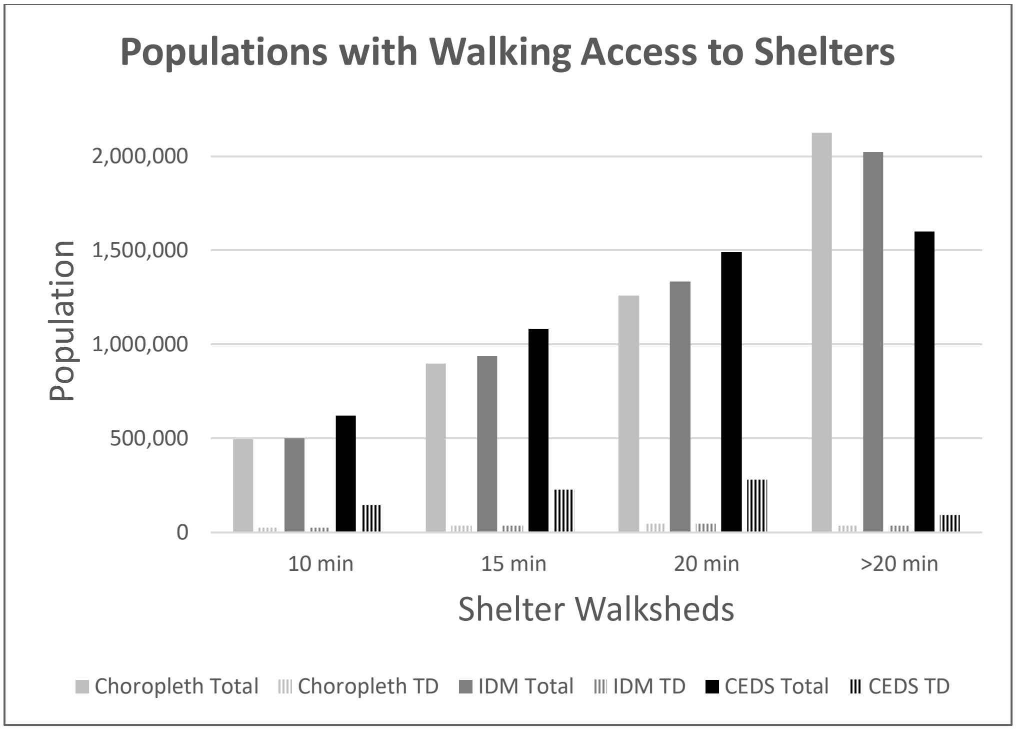

Figure 13. Populations with Walking Access to Shelters

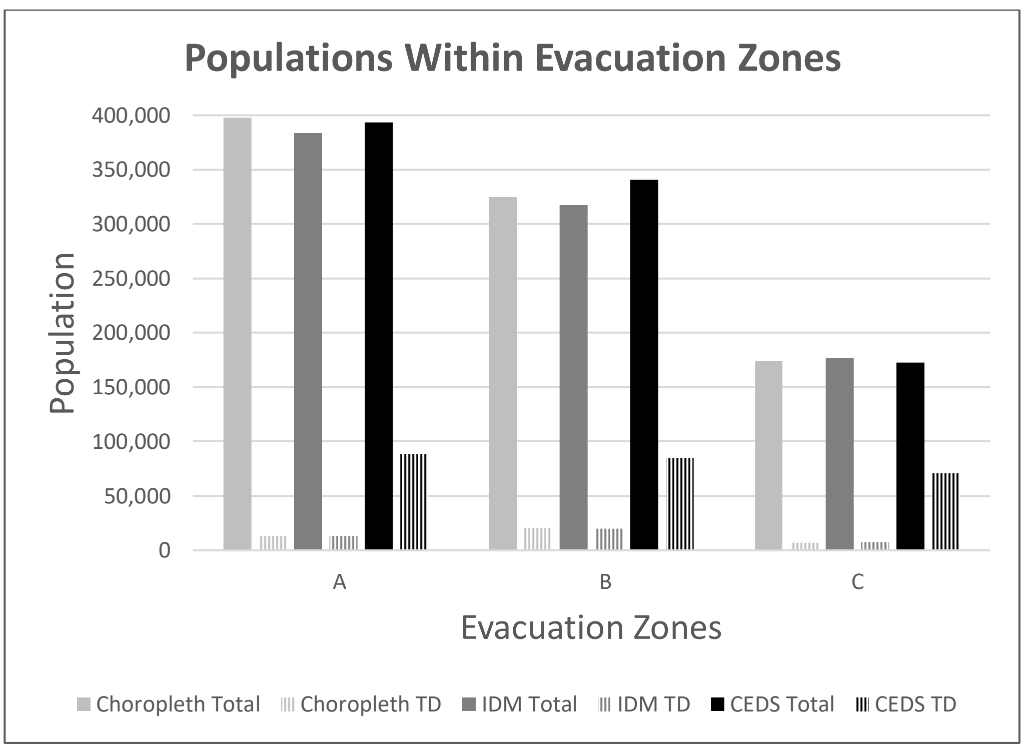

Figure 14. Populations Within Evacuation Zones

Table 7 and Figure 15 show the population estimates for those living both in an evacuation zone *and* greater than a 20-minute walk from a shelter. The CEDS method estimates a much higher proportion of these populations as TD: 15.3% compared to a more modest 4.4%. And while it estimates that this represents a smaller proportion of the total TD population (14.5% compared to 39.2%), this amounts to more than double the number of people estimated by the Choropleth and IDM methods (70,836 compared to 32,409).

Table 7. Populations Within Evacuation Zones and >20-Minute Walk from Shelter

	Choropleth			**IDM**			**CEDS**		
Within Zone, >20 Min From Shelter	TD	Total	% TD	TD	Total	% TD	TD	Total	% TD
	33,122	747,350	4.4%	32,409	733,125	4.4%	70,836	461,542	15.3%
Percentage of all TD	40.1%			39.2%			14.5%		

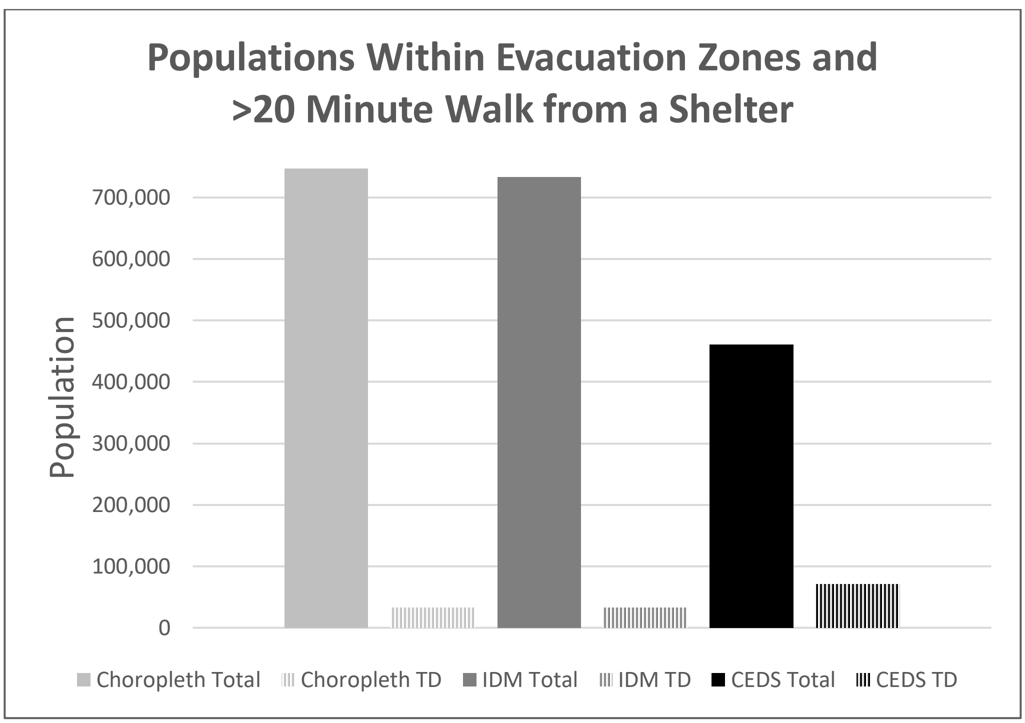

Figure 15. Populations Within Evacuation Zones and >20-Minute Walk from Shelter

It is worth reiterating that the CEDS method utilizes a slightly different definition of TD based on the results of the PCA. However, a scatterplot analysis reveals that the results of the binary method and PC1 are highly positively correlated (with a slope of 0.730 and significant at the 0.0001 level). Therefore, the dramatic difference in results is mostly due to the redistribution of population via the CEDS method, rather than the change in TD measurement.

Locating TD Populations

While each method results in different population estimates for TD residents within evacuation zones or within walking distance to potential shelters, they overwhelmingly identify the same cities and neighborhoods within the study area as having high levels of TD. The cities and neighborhoods that consistently display high levels of TD are Chelsea, Dorchester, East Boston, Framingham, Lynn, Mattapan, Revere, Randolph, Roxbury, and the South End of Boston. The CEDS analysis reveals additional areas that have high levels of TD, including Allston, Brighton, Everett, Hingham, Hyde Park, Malden, and Waltham.

While these analyses are not able to pinpoint specific TD households in need of evacuation assistance, they do demonstrate the areas in which residents may have a greater propensity to be vulnerable in an extreme weather event based on the general demographic and socioeconomic characteristics of that area. It is important to note that any analysis attempting to identify vulnerable populations will inevitably miss some people who do not fit the profile of the neighborhood in which they live. However, considering the inevitability of skewed population attributes, the TD figures predicted by these methods are likely to be underestimations, if anything.

Conclusion

In the next chapter, I will present the results of the interviews, detailing the neighborhoods and organizations targeted, the responses from the interviewees, and the insights gained from speaking with those involved in emergency management and community organizing.

5. Interview Results

To better understand the planning implications of transportation disadvantage (TD), I conducted semi-structured interviews with representatives from state-level agencies, local planning departments, and community organizations regarding my mapping results and TD in the communities they serve. The goal of these interviews was to ground truth the mapping results and to understand evacuation resources, if any, available to TD populations. I sent requests to ten agencies and community organizations, of which four responded; the interviewee organizations are listed in Table 8. Interviewees were provided with a digital version of the Cadastral-Based Expert Dasymetric System (CEDS) results which they could view online (see Appendix A for more information). All interviews were conducted in partnership with Melanie Gárate, the Climate Resiliency Project Manager at the Mystic River Watershed Association.

Table 8. Interviewee Organizations

Interview	Organization	Region
1	Chelsea Department of Planning and Development	Chelsea
2	Codman Square Neighborhood Development Corporation	Dorchester
3	Massachusetts Bay Transportation Authority (MBTA)- Office of Performance Management and Innovation (OPMI), Department of Environmental Affairs, Office of Diversity and Civil Rights	Statewide
4	Department of Homeland Security (DHS)- Cybersecurity and Infrastructure Security Agency (CISA)	Statewide

Chelsea Department of Planning and Development

Chelsea, MA is an extremely diverse city, serving as a gateway community for many of the region’s immigrants. Approximately 67% of Chelsea residents self-report as Latino with more than half of the population speaking Spanish as their primary language (Train 2020). Compared to the rest of the state, Chelsea residents are generally younger, with a higher percentage living in poverty. Over 70% of residents are renters and live in multi-family apartment dwellings or other high density housing. In addition, Chelsea's household sizes are higher than average, with more occupants per household. Chelsea is considered an environmental justice community, with many residents living in old housing stock (pre 1939) or in close proximity to contaminated sites or industrial facilities. A comparison of the three mapping results for Chelsea is shown in Figure 16, Figure 17, and Figure 18.

I discussed TD and evacuation planning in Chelsea with the Deputy Director of the Chelsea Department of Planning and Development. The Chelsea Department of Planning and Development provides a range of services for the city, including planning services, oversight of design, engineering, construction, and implementation, as well as civic engagement and participatory outreach (Train 2020). The Deputy Director confirmed that based on his knowledge of the city and its residents, the mapping results were representative of TD in Chelsea. However, he did discuss a few anomalies. He pointed out several parcels and areas that he would expect to have high TD but were not designated as such based on the analysis; these included the Innes Apartments, a public housing complex, and the Bellingham Hill neighborhood. Alternatively, he pointed out a higher income neighborhood that had been labeled as relatively high TD.

Evacuation zone A extends almost entirely across Chelsea, meaning Chelsea residents would be among the first to evacuate in the event of a strong storm. We discussed how the Planning Department's services would be impacted and how the city government would work to communicate with and help residents in such a scenario. Depending on the storm, several services could be severely interrupted, including transit, social services, healthcare delivery, and public works operations. If needed, many of these services could be deployed online but would require reliable internet access, which could be interrupted by extreme weather.

Chelsea tries to decentralize communications, disseminating information from multiple sources, using both English and Spanish and easy-to-understand language. There is lack of trust in government in the Chelsea community, so the City has begun working with "neighborhood block captains" to effectively communicate with residents; these volunteers are known and trusted by the community and are divided into key response areas such as food assistance, healthcare, or financial impacts. This program was created during the city's Municipal Vulnerability Preparedness process and was first deployed during the Covid-19 pandemic response. The city plans to assess the program's success following this first implementation.

Looking ahead, initiatives and legislation focusing on IT resiliency, increased government agility, and disaster training, could improve outcomes for residents as they face future extreme events. There is also potential in working with local high school students, improving preparedness for disasters with regular trainings targeting evacuation procedures, and working with additional community organizations like the Chelsea Collaborative or GreenRoots to increase outreach within Chelsea.

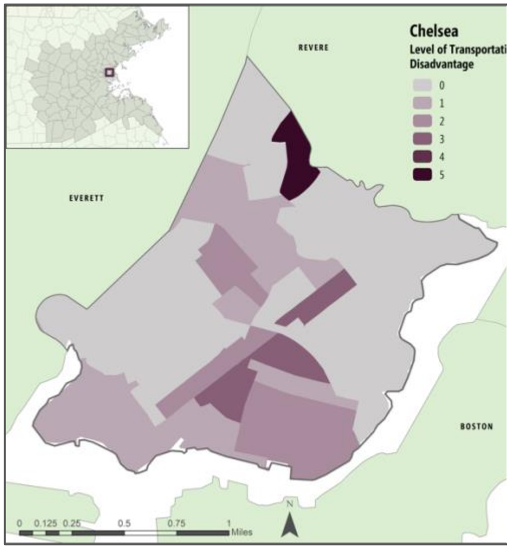

Figure 16. Transportation Disadvantage in Chelsea (Choropleth)

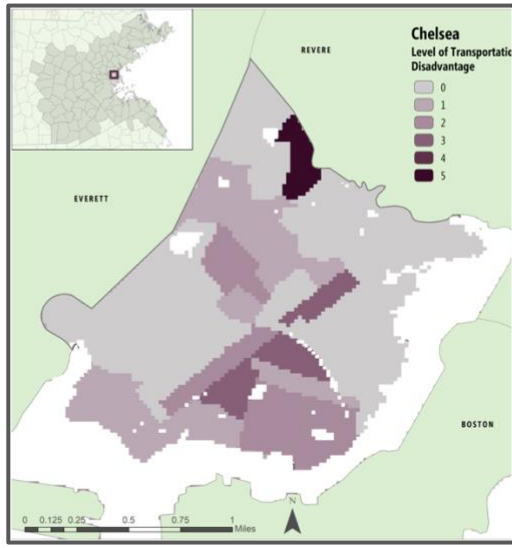

Figure 17. Transportation Disadvantage in Chelsea (Intelligent Dasymetric Mapping)

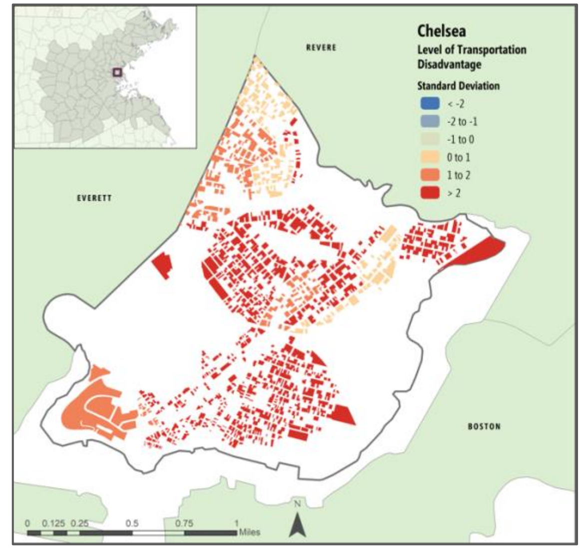

Figure 18. Transportation Disadvantage in Chelsea (Cadastral-Based Expert Dasymetric System)

Codman Square Neighborhood Development Corporation

Dorchester lies south of downtown Boston, extending from the edges of the South End and South Boston neighborhoods down to the towns of Milton and Quincy. A part of the City of Boston, Dorchester is home to one of the most diverse zip codes in the country (Kolko 2012). A majority of the residents are people of color, many of whom live at or below the poverty line and are housing cost burdened. Many residents live within walking distance to MBTA bus lines or the Fairmount/Indigo commuter rail line and depend upon these transit options to access their jobs downtown (Queeley, Forman, and Morales 2020).

I discussed my mapping results with three representatives from the Codman Square Neighborhood Development Corporation (NDC): the Director of Eco-Innovation, the Eco-Innovation Manager, and a Lead Organizer. Codman Square NDC works primarily on housing assistance, offering services that help residents stay housed, as well as economic and workforce development (Queeley, Forman, and Morales 2020). They also focus on issues of climate change and climate justice; one of their recent initiatives, called the "Eco-Innovation Initiative" focuses on "neighborhood scale sustainability that marries green, transit-oriented development (TOD), renewable energy, water conservation, alternative energy, sustainable food systems, waste reduction, and climate preparedness through resilience" (Codman Square NDC 2016).

While the map presented a "daunting picture" for their service area, these representatives generally agreed with the representation of TD in Dorchester

(Queeley, Forman, and Morales 2020). One area that they expected to have slightly higher levels of TD was along Morrissey Boulevard, which runs right along the coast and has poor access to transit. While flood risk and access to transit were not included in the vulnerability variables, they are likely to be correlated with income or race.

While only part of Dorchester lies within an evacuation zone, an extreme weather event would still have a great impact on the city and the services that Codman Square NDC provides. According to the interviewees, the main concerns during such an event would be safe access to shelters and health services, especially for elderly or unhealthy family members, and impacts on small businesses. As seen in the response to the Covid-19 virus, many local business owners would need to make the hard decision between preserving their investments and taking care of themselves. The priorities of the NDC would be to support their organizing staff that serve as critical intermediaries between the organization and the housing management companies and to help reduce the anxiety residents may feel in such a situation.

A recent fire in a senior housing complex put the need for disaster management into focus, as residents struggled to deal with this relatively small-scale emergency. While city officials came by following the event to provide training and to relay emergency protocols to residents (in multiple languages), the NDC has started to plan proactively for future emergencies. Some ideas include training to ensure residents know what to do in the event of an emergency and to consider how the NDC could provide options for residents beyond typical emergency shelters.

When it comes to future policies, the representatives from Codman Square NDC shared that emergency preparedness training for residents, as well as increased attention from the city and state when it comes to climate justice, could improve the ability of Dorchester residents to deal with an extreme weather event. As one representative put it, the City of Boston should “make lemonade out of climate change lemons,” and support the installation of additional green infrastructure, which would not only create a new workforce, but also allow people to directly benefit their neighborhoods and help the city meet its climate change goals (Queeley 2020). This kind of initiative could build on what the NDC has started in its Eco-Innovation District and expand it to other parts of the city, providing jobs and infrastructure improvements along with climate resiliency.

Massachusetts Bay Transportation Authority

In close coordination with the Massachusetts Department of Transportation (MassDOT), the Massachusetts Bay Transportation Authority (MBTA) provides multi-modal public transit and paratransit services to 175 cities and towns in Eastern Massachusetts (and parts of Rhode Island) (MBTA n.d.). It is the largest and highest ridership regional transit authority in the Commonwealth. During an average weekday, 1.18 million trips are taken on MBTA buses, light rail, heavy rail, commuter trains, ferries, or paratransit vehicles (MBTA 2019). Behind the scenes of MBTA service and operations are multidisciplinary staff across numerous departments focusing on long range planning, including climate resiliency, measuring service performance, supporting reporting obligations, and ensuring compliance with civil rights obligations through investigations, equity analyses, and legally compliant business practices.

I discussed my research with five MBTA employees, representing the Office of Performance Management and Innovation (OPMI), the Department of Environmental Affairs (DEA), and the Office of Diversity and Civil Rights (DCR). OPMI is a joint MBTA and MassDOT department, responsible for performance management and reporting across MassDOT's four divisions: Highway, Aeronautics, Registry of Motor Vehicles, and Rail and Transit (including the MBTA) (Mass.gov 2020d). DOE is focused more on environmental compliance with federal regulations as well as looking at engineering resiliency and the effects of climate change on the system's infrastructure. Lastly, ODCR focuses both internally, ensuring non-discrimination in staffing and hiring, as well as externally, fulfilling non-discrimination obligations to the public, through monitoring programs, services, and activities for any possible disparities and through inclusive public engagement.

While the interviewees did not disagree with the vulnerability attributes included in the TD analysis, they were interested to learn that the definition did not include access to transit. As transportation professionals, this was their first reaction to hearing the term “transportation disadvantage.” One representative found the term to be rather passive, and wondered if there would be a way to capture not only demographic and socioeconomic trends, but also to think about the local political climate and will of politicians to proactively enhance transportation and connectivity; for example, even an area with seemingly low TD could be plagued by inaction or denial of the necessity of climate change preparedness. When it came to the mapping results, the MBTA representatives believed the results generally reflected what they knew about the study area; however, they wondered if there was a way to better represent more recent population shifts and immigration patterns that may not be captured in census data (Lyons-Galante et al. 2020).

Compared to a single municipality, the MBTA would face different challenges in the event of extreme weather. The size of the impact would depend largely on the storm’s effect on the power network. While the MBTA operates its own power plant in South Boston that can power the electrified network in an emergency, outages to individual stations could affect operations. In addition, there is always the risk of tracks or bus routes flooding. During such an event, the MBTA would use a variety of strategies to communicate service disruptions to riders, including web communication, Transit app announcements, physical and electronic signage, radio announcements, and other avenues. Staff are trained to understand that communication strategies must be adapted to effectively reach diverse populations. For example, a four factor analysis is used to guide communications and ensure access for those with limited English proficiency (LEP). The four factors are as follows:

6. The number or proportion of LEP persons eligible to be served or likely to be encountered by a program, activity, or service of the recipient or grantee.
6. The frequency with which LEP individuals come in contact with the program.
6. The nature and importance of the program, activity, or service provided by the recipient to people's lives.
6. The resources available to the recipient and costs.
   (US DOT 2016)

Current investments in real time translation services will increase the ability of the MBTA to communicate with diverse populations. The MBTA also partners with advocacy groups and community-based organizations across the service area to help disseminate information. They maintain a database of approximately 4,000 such organizations that can help push notices out to the populations they serve (Lyons-Galante et al. 2020).

In the event of a disaster, ridership tends to decline on MBTA lines; however, it is likely that those who are normally transit-dependent will remain so during an emergency (Lyons-Galante et al. 2020). The MBTA has a Security and Emergency Management Department focused on addressing such emergency situations. Their work is both proactive, coordinating with the Massachusetts Emergency Management Agency to identify where and when emergency vehicles could be deployed, and reactive, responding to emergency events in real time by rerouting busses and assessing station access and functionality. MBTA staff, especially those in operations, are offered extensive emergency management training and departments often select point persons responsible for monitoring emergency events.

Outside of emergency management, the MBTA is trying to increase service by retooling several bus lines to better serve higher population densities and vulnerable populations through the Better Bus Project (MBTA, n.d.). OPMI is also looking at which bus lines connect to important social services and how to ensure these lines remain operational during emergencies. Lastly, DOE may conduct vulnerability assessments as part of their climate work, looking at the system from an infrastructural angle and determining which lines are most susceptible to extreme weather.

In the future, certain policies and programming activities could help increase the resiliency of the MBTA system. For example, the implementation of infrastructural requirements related to extreme weather could support engineering decisions. Adjustments to the procurement processes could help facilitate communications to diverse populations where document translation and/or language interpretation services are needed immediately to address an emergency situation but must be competitively procured via a process designed to take several weeks. Training could be expanded to support staff or riders themselves. There is a lot to learn each time a disruption affects the system; for example, as a result of the Covid-19 pandemic, the MBTA is monitoring changes in ridership by mode, line, station, and time of day (MBTA 2020). The MBTA aims to apply these lessons moving forward, with the goal of effectively and safely responding to future emergency events as they arise.

Department of Homeland Security

The Department of Homeland Security (DHS) is a federal department that was created in response to the attacks on September 11, 2001; its mission is "to secure the nation from the many threats we face" (DHS 2019). The Cybersecurity and Infrastructure Security Agency (CISA) is a division of DHS "responsible for protecting the Nation's critical infrastructure from physical and cyber threats" (DHS, n.d.). DHS follows the same regional model as the Federal Emergency Management Agency (FEMA) so Massachusetts and the other New England states are considered Region 1.

We spoke with the Region 1 Training and Exercise Coordinator about the mapping results. The main responsibility of this Coordinator is to work with both public and private stakeholders—which may include entities such as municipal governments, houses of worship, or private industries—to test and critique their response plans for various emergency scenarios. These plans typically aim to address responses to four of the 16 critical infrastructure sectors: communications, transportation systems, energy, and water and wastewater systems. The Coordinator conducts a sort of stress-test, pushing the assumptions of the stakeholder's response plan and helping them learn lessons before actually facing an emergency head on.

The interviewee was familiar with the concept of TD and found the mapping results to be representative based on her knowledge of the study area. She remarked that those areas that appeared to be “transportation islands” closely resembled known areas considered to be “food deserts” and that it is likely that many areas experience several kinds of disadvantage. She suggested displaying and analyzing access to evacuation routes as well, to demonstrate further disadvantage in the event of extreme weather.

Rather than assisting during an emergency, CISA focuses on preparation, planning, and data analysis leading up to an emergency scenario. When planning ahead, they aim to be “scenario agnostic,” or in other words, they do not provide too many details about the emergency scenarios a response plan is being tested against. From their perspective, any emergency has the potential to threaten critical infrastructure, and the response from stakeholders should be appropriately aggressive regardless if they are faced with a hurricane, blizzard, or pandemic.

The interviewee mentioned two ways in which resilience could potentially be improved for TD populations in an emergency. First, she suggested analyzing the farebox recovery ratios of different transit lines in the Boston metropolitan area. The farebox recovery ratio refers to the ratio of operating expenses met by fare payments paid by riders (FTA 2017, 21). These ratios vary by mode and could shed light on which systems depend on high ridership to function. Comparing this with the distribution of TD populations could further expose which areas may be vulnerable to lapses in service during an emergency. Resilience could also be improved by increasing the level of engagement with the public. For example, in some parts of the country, advisory groups representing neighborhoods help funnel local issues up to the state legislature. While this kind of grassroots engagement is certainly not nonexistent in Massachusetts, it could be increased to help create a cohesive set of priorities at the state level for TD populations.

CONCLUSION

In the final chapter, I will discuss the mapping and interview results presented in Chapter 4 and Chapter 5. I will compare my results with existing data and estimations, discuss themes that emerged during my research, policy implications, research limitations, and ideas for future research.

6. Discussion and Conclusion

This thesis seeks to better understand where transportation disadvantaged (TD) populations are located in the Boston metropolitan area and their relative risk to extreme weather events. In parallel, this research hopes to relate the mapping results to the policy and planning experiences in emergency management agencies and the lived experiences of those communities most at risk. Both the mapping and interview processes reveal results that are notable, if not surprising, based on anecdotal knowledge of the Boston area. 14% of the population in the study area has a high propensity to be TD, and of these people, 14% live within an evacuation zone and farther than a 20-minute walk from a potential shelter. Compared with estimates from the Massachusetts Emergency Management Agency (MEMA), these numbers are significantly higher and could represent a severe underestimation in the amount of people that could require assistance during an evacuation.

Mapping Themes and Discussion

As expected, there are notable differences in the results of the three mapping methodologies. The results improve in accuracy and detail, both visually and quantitatively, as the methods utilize increasingly finer-grained layers and processes to represent population distribution and levels of TD. Both the Intelligent Dasymetric Mapping (IDM) and Cadastral-Based Expert Dasymetric System (CEDS) methods provide improvements in representing population distribution, purposefully not assigning population to areas that are generally uninhabited or non-residential. However, the CEDS system further increases accuracy by only assigning population to residential parcels, while the IDM system may assign population to any areas of high-intensity land use, whether residential, commercial, or industrial. This erroneous population representation can be seen in the IDM results in areas like the Irving Oil Terminals in Revere or the southwestern part of Lynn, which is heavily commercial. In addition, the CEDS system uses a principal component analysis (PCA) to score TD, which minimizes the errors in estimations that may arise from the binary method. For example, the binary method's threshold could skew population estimations depending on the distribution of the underlying data for each block group.

For the most part, the specificity of the CEDS system results in large increases in population estimates for both total and TD population. There are a few reasons that could account for this drastic difference. First, while the IDM system redistributes population density based on intensity of land use, it still assumes uniform density across similar land use designations. Therefore, there is averaging of population density across a particular area. In contrast, the CEDS system estimates population on a per-parcel level, based on either the number of residential units or the residential area of that parcel. Therefore, the CEDS method is better suited to estimate population in multi-family buildings, such as apartment buildings, in which lower-income populations often live. Since these buildings typically house a much larger number of people per parcel than single-family homes, the CEDS method results in higher TD population estimates, especially in high population density locations such as Boston, Cambridge, and surrounding towns. Lastly, the CEDS system only analyzes parcels with residential classification codes, reducing the possibility that high-intensity commercial areas are included in the analysis. These factors amount to a more specific allocation of population, based on known residential parcels and building sizes.

As mentioned previously, the CEDS system uses a slightly different TD scoring system, based on the results of the PCA, which helps control for the high correlation between the vulnerability attributes. However, the significant correlation between the first principal component and the binary scoring suggests that the difference in population estimates between methods is mainly due to the population redistribution methodology. One figure the CEDS system predicts very differently is the total population living within an evacuation zone and farther than a 20-minute walk from a shelter. The CEDS system results in a considerably lower population estimate (461,542 compared to 733,125 predicted by the IDM method), but this is likely just a reflection of the accuracy of the CEDS system.

COMPARING EXISTING DATA AND ESTIMATIONS

This vulnerability analysis is not the first of its kind in the Boston area. In an effort to further understand the mapping results, I visually compared my results with previous studies of vulnerability, including work done by Climate Ready Boston, the Metropolitan Area Planning Council (MAPC), and the Massachusetts Executive Office of Energy and Environmental Affairs (EOEEA).

Climate Ready Boston has produced an online, interactive map of Boston with layers for high tide projections, coastal flood risk, storm water flooding, heat, and social vulnerability (City of Boston 2020). Each of the social vulnerability attributes, which include Low Income, People of Color, Limited English, Disability, Medical Illness, Elderly, and Children, overlap significantly with areas of high TD. These attributes are commonly seen in the Allston, Brighton, Dorchester, East Boston, Roxbury, and South End neighborhoods.

MAPC's "Climate Vulnerability in Greater Boston" analysis maps vulnerability indexes for heat, flooding, and future flooding (MAPC n.d.). Many areas that are identified as having high TD, such as Chelsea, East Boston, Lynn, and Revere, also have moderately or extremely high vulnerability to riverine and storm surge flooding as identified by MAPC.

EOEEA has produced an Environmental Justice Viewer, which is an interactive map displaying census block groups classified as Environmental Justice (EJ) areas (Mass.gov 2020a). According to their definition, a block group is identified as EJ if any of the following are true: "annual median household income is equal to or less than 65 percent of the statewide median ($62,072 in 2010); 25% or more of the residents identify as a race other than white; or 25% or more of households have no one over the age of 14 who speaks English only or very well (English Isolation)" (Mass.gov 2020a). Overwhelmingly, the areas with high TD also exhibit characteristics of EJ communities, especially in and immediately surrounding downtown Boston.

I also compared my results with historic redlining maps, produced by the University of Richmond (Nelson et al. n.d.). The areas of high TD closely resemble the boundaries of historically redlined areas in Boston. Except for some areas in Cambridge, Somerville, and downtown Boston, those neighborhoods that were redlined still see very high TD populations today. A screenshot of the University of Richmond site is show in Figure 19.

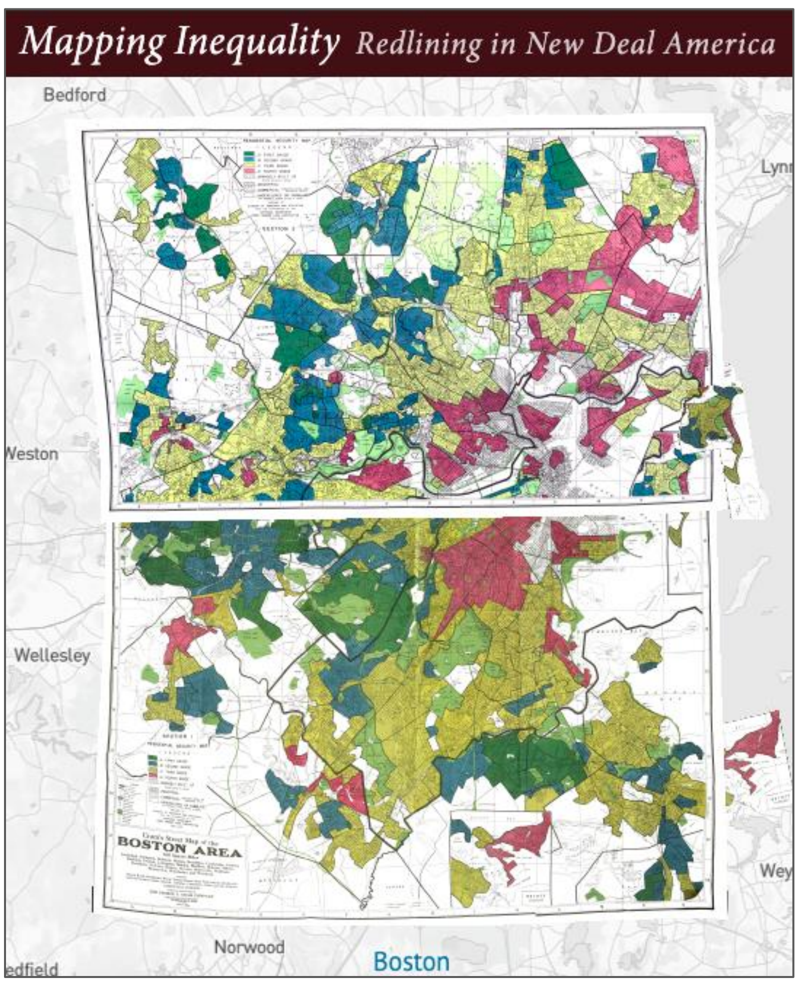

Figure 19. Historic Redlining in Boston

Lastly, I compared my results with the estimates in the *Critical Transportation Need (CTN) Evacuation Operations Annex* to the *Statewide Evacuation Coordination Plan*. As previously mentioned, MEMA estimates that 2% of the population in evacuation zone A and 1% in zone B will require assistance in a “notice incident” such as a hurricane. In a “no-notice incident” as many as 6% of the population will require assistance (MEMA 2019a, 16). In comparison, my methodology has determined that as much as 22% of the population in zone A and 25% in zone B could be TD, or of “critical transportation need.” While my analysis does not distinguish between “notice” and “no-notice” incidents, it demonstrates a potentially large underestimation on the part of MEMA of how many people may require assistance in the event of an evacuation.

Interview Themes and Discussion

Overall, the interviewees confirmed the locations that are identified to be TD in this study. Based on their knowledge of the Boston metropolitan area and neighborhoods within, the distribution of disadvantage was not surprising to them. However, several interviewees suggested improving upon the mapping by adding additional layers, such as flood zones or evacuation routes, or by introducing additional vulnerability attributes to the traditional definition of TD, such as access to transit. Interviewees also expressed a desire to include additional populations as they shift and change in today’s rapidly urbanizing and gentrifying context.

Whether a community organization or state-level agency, the organizations were all most concerned with essential infrastructure and services in the event of extreme weather. All organizations expressed concerns over the effects of extreme weather on energy and transportation systems and how potential outages or lapses in service could affect the delivery of social or medical services. At the community level, concerns were focused on individual residents and small businesses, while at the state level, the focus was more holistic, thinking broadly about the entire network. It was encouraging to learn that all organizations had detailed communications plans, with attention to communicating with diverse populations speaking multiple languages.

Looking ahead, each organization expressed a desire to increase proactive planning and training, and to capitalize on existing projects in an effort to increase resiliency. For example, the Eco-Innovation District in Dorchester and the Massachusetts Bay Transportation Authority's (MBTA) Better Bus Project are not meant to directly tackle extreme weather preparedness; however, their benefits (including green infrastructure and retooled bus routes) would certainly be welcome in the event of an emergency. Additional proactive measures included increasing IT resiliency, government agility, and infrastructure requirements to ensure efficient responses when extreme weather events occur.

It appears that additional training and communication at the neighborhood level is something both the community and state-level organizations would encourage, as a way to both engage residents and to better prepare them for emergency events. While it seems that the MBTA is already partnered with many advocacy organizations to assist with communicating MBTA disruptions and announcements, it could be beneficial for these partnerships to allow more two-way communication so that community members can also offer ideas and provide insight into the problems they are facing.

Overall, it is clear that the organizations interviewed, and many others, are thinking more about climate change resiliency and the threats that extreme weather poses to our critical infrastructure. However, while these organizations are taking steps to increase resiliency, it appears they may be doing so at a broad level, without attention specifically to those who have high TD. Additional conversations with those departments and organizations more closely aligned with evacuation planning may have been able to offer more insight into this question.

POLICY IMPLICATIONS

While this research has revealed that many local organizations are committed to serving diverse populations equitably, they do not appear to be working closely with TD populations in the Boston metropolitan area. These populations are certainly not ignored, as MEMA pays special attention to CTN populations, and other organizations like the MBTA and the Department of Homeland Security are aware of contextual factors in transit and emergency response planning. However, it remains unclear if and how municipalities are adequately estimating and accounting for these populations in evacuation and emergency planning.

The mapping methodology developed in this thesis could help planners, at all levels of government, to more accurately predict areas with high TD and to appropriately tailor evacuation plans and target resources to ensure that those at the highest risk are provided adequate evacuation assistance. For example, leading up to an evacuation, outreach could be increased in areas determined to have high TD; information campaigns could be pushed via non-traditional channels, such as advocacy organizations or door-to-door canvassing, in multiple languages, to increase the level of trust and communication. Evacuation routes and shelter assignments could be adjusted in these areas to ensure there is enough capacity and efficient access. During an evacuation, additional vehicles could be dispatched to these high TD areas so that those who do not have access to personal vehicles could be safely transported to Evacuation Assembly Points or shelters.

The CEDS analysis is feasible in any city that has access to census and parcel data. Although it is more time consuming than the other methods, the mapping tools it utilizes are not beyond the technical capability of local planning agencies. The results could be updated as new census information becomes available or new vulnerability attributes are added. Conducting a principal component analysis could potentially require more bandwidth depending on software availability but it would considerably strengthen the analysis.

In addition to conducting mapping analyses, evacuation planning for TD populations should be combined with other identification methods, such as in-person outreach, registries, or surveys, that will allow identification on a household level (or as close to a household level as possible). This could help planners understand where to dispatch vehicles with handicap accessibility or where to direct special medical attention. In this respect, advocacy organizations, faith-based organizations, and other community partnerships could be extremely helpful in providing this neighborhood-level information.

Research Limitations

While I took care to reduce errors in this analysis, several limitations affected both the data and process. Beginning with the spatial analysis, the binary coding for vulnerability attributes used to identify levels of TD is limited in its approach. There are always anomalies to census geography trends and this approximation of TD inevitably misses some members of the population and counts others who are not disadvantaged in reality. Therefore, the resulting population numbers for this method are still very much an estimate, since they include populations that are not disadvantaged but could live in areas with means above the threshold for certain vulnerability attributes. On the other hand, this method could entirely miss vulnerable populations that reside in areas that do not exhibit vulnerability attributes on average. The PCA was used with the CEDS method in an effort to address some of these limitations.

Several spatial layers are also limited in their level of detail or attributes included. For example, the National Land Cover Database raster layer, while relatively varied, is still rather coarse. For example, a shopping center could be coded as medium- to high-density—the same as the coding for a block of apartment buildings. In addition, the land cover designations are not binary in reality—an evergreen forest may include residential plots in some areas, and in others it may not.

The parcel data is similarly problematic, in that the state-level parcel layer and Boston parcel layer do not share similar attributes, and several pre-processing steps, as well as a join with additional MAPC data, are required to render the parcel layers usable for this analysis. This may not be the case in all cities, but it underscores the overarching need for good data management and documentation. In addition, I learned during the interview process that public housing complexes are labeled under the “exempt” use code, *not* “residential,” which means they are not included in the parcel analysis. Other exempt parcels include those owned by hospitals, universities, and charitable organizations. In future studies, special attention to the locations of these parcels could prevent this deduction of relevant data. Lastly, the use of public schools as a proxy for shelters is an approximation; using known locations for all emergency shelters and evacuation assembly points would be more precise. I learned in the interview process that a layer of National Shelter System Facilities is available through the Homeland Infrastructure Foundation–Level Data (HIFLD) database (HIFLD 2020). This would certainly paint a clearer picture of areas that may be particularly vulnerable in the event of an evacuation.

While it attempts to address the Modifiable Areal Unit Problem, these mapping methods still rely on census data to assess locations of TD populations, making them all susceptible to the typical limitations of aggregated data (Fotheringham and Wong 1991). For example, land-use and parcel boundaries do not necessarily line up with census boundaries from which the level of TD is calculated, affecting how census data is assigned. These small errors can trickle down to the final calculations, skewing population counts for TD populations.

Total population estimations are also slightly skewed between the three methods, due to the ways in which population is redistributed via the IDM and CEDS systems. Due to rounding, the total and per block group population in both the dasymetric methods is slightly off from the census recorded total. In the IDM method, which produces a lower total population, this discrepancy is minimized by implementing intermediate calculations which preserve the continuous population density values. In the CEDS method, which produces a higher total population, the use of continuous fields in field calculations prevents an even larger increase in total population estimates.

Looking Ahead

There are several opportunities for future studies to expand and improve upon this methodology. First, when assessing levels of TD, future research could include additional vulnerability attributes such as access to transit, educational attainment, pre-existing health conditions, mental health, or employment status. If available, population data concerning tourists, undocumented immigrants, and those experiencing homelessness, could also be included to highlight the vulnerabilities these populations face.

Future research utilizing the CEDS method could implement several pre-processing steps to better locate populations. One method that has potential in the Boston metropolitan area is that put forth by Strode et al. to better account for group living situations such as nursing homes, college dormitories, or military bases (Strode, Mesev, and Maantay 2018). This method also addresses the issue of spatial incongruency between parcel and census geography boundaries.

When assessing relation to extreme weather risk, future research could compare hurricane inundation zones, flood maps, or evacuation routes along with, or in place of, evacuation zones. While evacuation zones are created based on these layers, such a comparison could provide slightly different results. Alternatively, other metrics of extreme weather unrelated to hurricanes could be used, such as wildfire or drought risk. In any extreme weather context, it would be helpful to utilize a layer of current emergency shelters, such as the one available through the HIFLD Database.

Lastly, additional qualitative interviews with organizations or departments such as the Volpe National Transportation Systems Center, MEMA, the MBTA Security and Emergency Management Department, or Transportation for Massachusetts could help further inform this discussion, offering additional perspectives on how TD populations are included in emergency planning.

Conclusion

According to this analysis, hundreds of thousands of residents in the Boston metropolitan area may be transportation disadvantaged. This vulnerability affects these residents' lives on a daily basis, as they rely on transit, paratransit, walking, or biking to travel to work, run their errands, or visit friends and family. For some, their level of TD may be so high that they are unable to leave their homes at all without a great deal of assistance. In the event of an emergency, this disadvantage is increased tremendously, as residents may be required to evacuate their homes and make their way to a shelter. Alternatively, in a different kind of emergency scenario, such as the Covid-19 pandemic occurring at the time of writing, those who are TD may not be able to access essential services, food retailers, or drive-through testing sites. Ironically, both stay-at-home and evacuation orders are likely difficult for TD populations to adhere to due to their reliance on transportation assistance.

In Massachusetts, a municipality is technically responsible for providing transportation assistance to these residents so they can safely reach a local shelter; however, this thesis reveals that many more people may require assistance than MEMA estimates and the resources offered to municipalities to identify TD populations are limited. It will take increased attention to these populations, in the form of mapping analyses using the most up-to-date information, community outreach, and proactive infrastructure management to avoid a disaster response like Hurricane Katrina in New Orleans. Massachusetts has been lucky to avoid the brunt of major storms in the past few decades, but the state is bound to be faced with a powerful storm at some point in the near future. As planners, we must proactively prepare for this event, so when the time comes, everyone—including the most vulnerable and transportation disadvantaged—are able to get out of harm's way.

APPENDIX A – ONLINE MAP

CARTO, an online GIS platform, was used to provide interviewees with an interactive version of the Cadastral-Based Expert Dasymetric System (CEDS) results. This map can be accessed <u>here</u> and a screenshot is shown below in Figure 20.

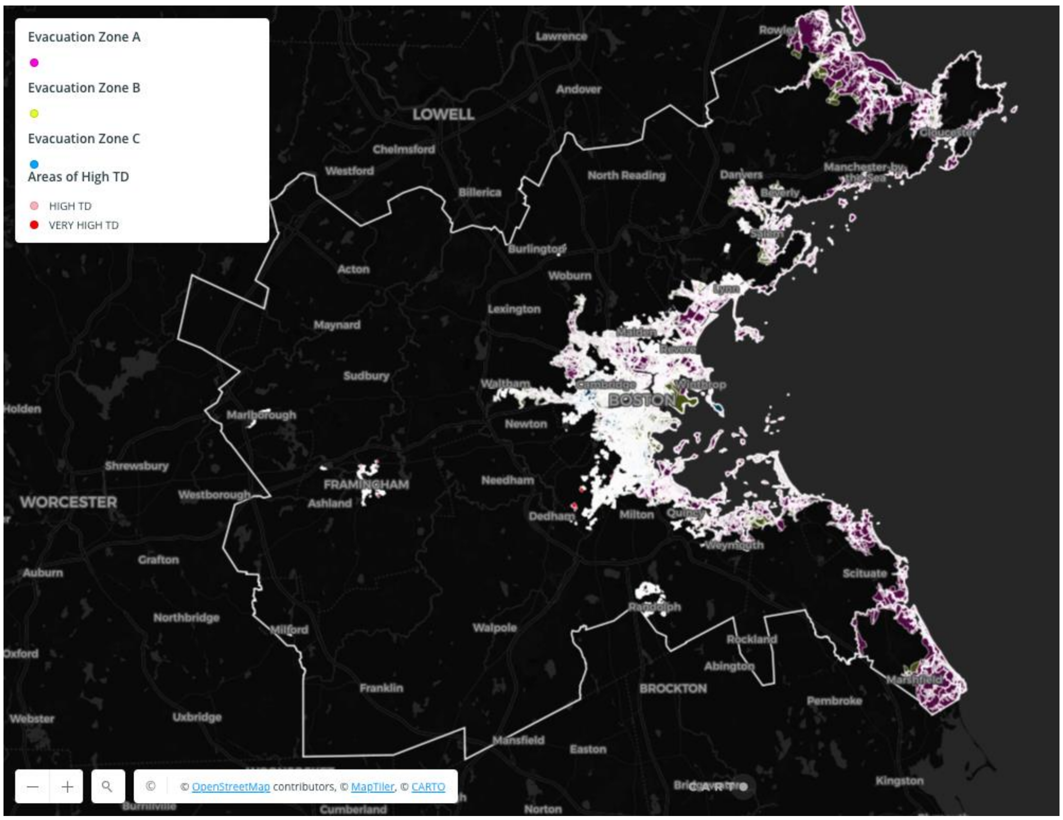

Figure 20. Screenshot of CARTO Map

Appendix B – Interview Questions

Background Information

1. To begin, can you please go over the populations your organization serves and their general characteristics?
2. What services do you provide and where?

Transportation Disadvantage

Transportation Disadvantage (TD) can be described as a combination of many factors, some socioeconomic, some environmental, and others behavioral. TD populations commonly include those who are carless (whether by choice or not), minority, low income, elderly, disabled, those with limited mobility or health problems, homeless, children without adults present, or those with limited English proficiency. Access to transportation systems, such as public transit, infrastructural or geographical barriers, such as bridges or sidewalk availability, and social connectivity can all play a role in TD.

3. Do you generally agree with this definition? Do you have anything to change or add?

Mapping

This map displays areas in which residents have a high propensity to be TD. It is based off of seven vulnerability attributes: children, elderly, poverty, vehicle access, disability, English proficiency, and race.

4. Based on your understanding of the neighborhood(s) your organization works with, do you think this accurately represents the TD folks in this area?
    a) Are there areas that appear to have higher or lower TD than the map indicates based on your knowledge?

Storm Scenario

Imagine there is a very heavy summer storm of 6 inches of rainfall over two days that causes flooding of roads and parks causing disruptions to public and private areas and causes multi-day power outages in this area. Remember the storms of 2018 in the area (the “Bomb cyclone”).

5. What would be the impacts on the people that you serve?

   a) How would you disseminate information to people in the case of an emergency? How would that differ from normal communications about programs or services?
   b) Specifically, how would you communicate with those who do not have access to technology, who do not speak English, or who have other communication barriers?
6. Would you be able to provide your services adequately? Why or why not?
7. How would it affect demand for your services?
8. What would be the barriers to obtaining (general) social services for the populations you serve?

Policy Implications

The Massachusetts Emergency Management Agency provides an Annex to their Comprehensive Statewide Evacuation Coordination Plan specifically for populations with “Critical Transportation Need” (CTN). MEMA defines CTN populations as the “segment of the population that lacks personal transportation and requires government-provided transportation assistance to evacuate out of an at-risk area to a designated shelter.” This plan assumes that 2% of the population in hurricane evacuation zone A and 1% in zone B will require assistance in a “notice incident” such as a hurricane. In a “no-notice incident” as many as 6% of the population will require assistance. A municipality is responsible, at a minimum, for providing transportation assistance to CTN evacuees either from their private residences or from an Evacuation Assembly Point (EAP) to a local shelter. EAPs are designated locations to which CTN populations will be directed in the event of a large evacuation.

9. Were you aware of these policies? Based on your knowledge of emergency and community resources, how else are TD populations addressed in evacuation planning?
   a) What resources exist for these populations (or any populations you serve) in preparing for and/or following through with an evacuation?
   b) Have you experienced an evacuation event in which you were assisting or providing resources for TD populations?
10. What legislation/policy would improve the resilience of the populations you serve during extreme weather (in a dream world)?
    a) What adaptation policies would you like to see implemented to help the people you serve (in a dream world)?
11. What kind of programming would help the populations you serve, and the broader community they live in, become more resilient? (training, drills, educational events, etc.)

Other Organizations

12. What other organizations/groups do you work with often that might be helpful in reaching TD populations or other underserved people in your sector?
13. What other organizations do you know that add to the social safety net?
14. Who else might be helpful for us to talk with?

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